National Aeronautics and Space Administration

Marshall Space Flight Center

Core Capabilities and Services

marshall

Launching the Future of Science and Exploration

Director’s Letter

From the Director

Marshall Space Flight Center has a proud legacy of supporting NASA’s missions of science, exploration and discovery. Our contributions have been many, reflecting the enormous challenges and enormous potential of spaceflight that this nation embraced more than 50 years ago when NASA and Marshall were created.

It is no surprise that Marshall’s contributions have been so broad and sustained and its record so successful. The environment of space is so alien, the challenges so unique, and the solutions required so ingenious that they require a wide array of capabilities, both mutually dependent and mutually supportive.

In response, Marshall developed world-class capabilities in areas such as propulsion, materials, space environments, avionics, advanced manufacturing, life support, testing, systems integration, and many more. As NASA’s mission and requirements have evolved, Marshall has evolved to support them. This center continues to provide the broad technical expertise and consolidated cross-cutting capabilities to affordably, efficiently support the needs of the Agency, our government and commercial partners, and the nation.

It’s an expression of the Marshall Team’s diverse passions for spaceflight that the center’s capabilities today encompass space transportation, sustaining human life, and scientific exploration from the distant reaches of the universe to the surface of our home planet.

The men and women of Marshall Space Flight Center are the true measure of its capability, and they continue to advance the frontiers of science and technology. Every day, we face never-been-done-before challenges with pride and enthusiasm. I salute the NASA heroes who forged the way, those here today, and those yet to come. And I am humbly thankful to be part of Marshall’s amazing history.

Patrick E. Scheuermann,
Center Director

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Marshall Space Flight Center

Propulsion

Propulsion

- Liquid Propulsion Technology and Development

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Liquid Propulsion Technology and Development

Affordable Development for the Next Decade

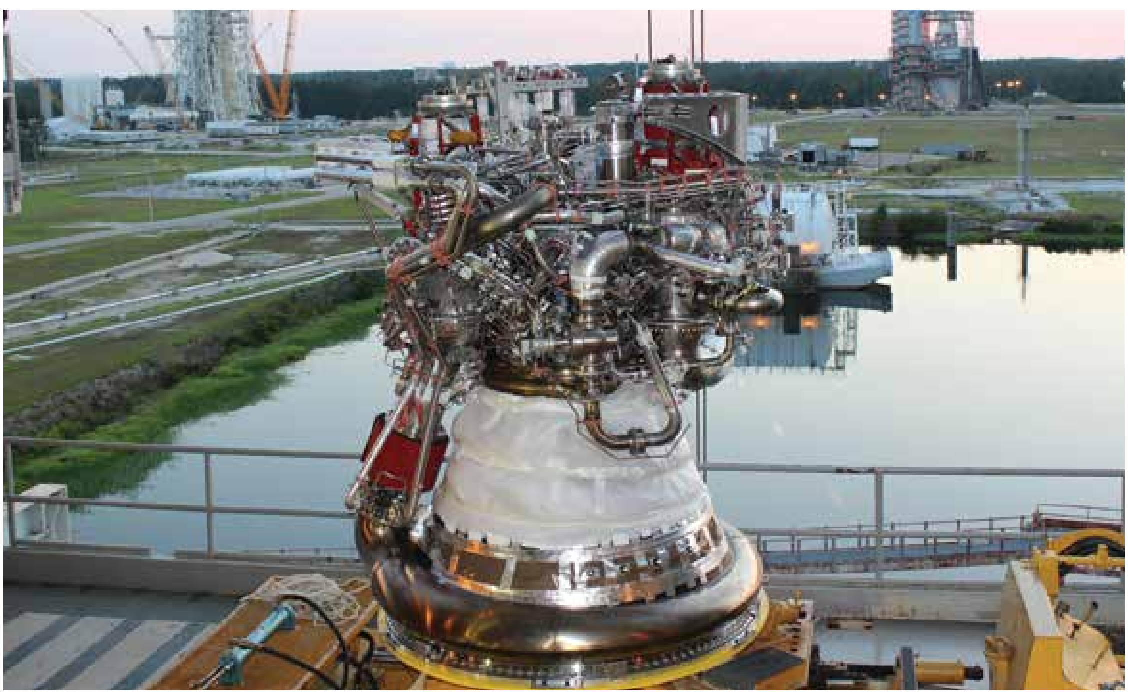
Development of new launch and in-space liquid propulsion solutions for the exploration needs of the future hinges on purposefully maturing design approaches to provide affordable development paths. Marshall draws on decades of experience with almost every propulsion system developed, both small and large, and is applying innovative approaches such as additive manufacturing to shorten development cycles, improve integration of propulsion systems with vehicles, and validate new technologies prior to production.

Marshall provides affordable, comprehensive liquid propulsion capabilities that meet the needs of NASA, Department of Defense, and private industry — from conceptual design and development and testing to mission support. Marshall's unique capability to design, fabricate, test, and analyze liquid propulsion systems on site allows customers to optimize resources, consolidate project management, and reduce risk.

The Center's expertise ranges from small pressure-fed to large, complex pump-fed rocket engines that support liquid propulsion requirements for Earth-to-orbit, beyond-Earth orbit, and in-space missions. Marshall's technical expertise and experience are matched with the Center facilities, laboratories, and equipment needed for any aspect of liquid propulsion system development.

At-A-Glance

Affordable development of liquid propulsion systems is critical to remaining nationally competitive and to advancing exploration goals. Cost-effective propulsion development preserves a larger portion of available budgets to accomplish scientific and exploration goals. Marshall Space Flight Center leverages its significant experience, broad discipline expertise, and comprehensive facilities to ensure reliable and affordable liquid propulsion solutions to meet Agency and national priorities.



Marshall continues to improve performance of the J-2X engine to meet future mission needs.

Since development of operational space transportation systems and architectures represents long-term, often generational, investments of public resources, Marshall's management, oversight, and insight roles for complex propulsion system development and operations represent critical safeguards and stewardship of these investments. Use of advanced manufacturing methods, integrated design/development strategies, and acceptance of risks on early development hardware drive down costs and improve system performance and reliability.

Drawing on History To Design the Future

For over five decades, Marshall's scientists and engineers have designed, developed, integrated, and sustained liquid propulsion systems that have set the pace for historic advancements in space exploration. Building on the past, Marshall inspires confidence in future launch vehicles, including the heavy-lift Space Launch System (SLS) now under development. Leveraging Marshall's success in previous propulsion system development reduces schedule and cost requirements in propulsion development for a range of future applications, including SLS and in-space mission needs.

Apollo Program — Marshall developed Saturn's F-1 engines from testing to flight and the second stage J-2 engines from earliest concept development to flight. The F-1, to this day the most powerful single-nozzle liquid-fueled engine ever built, is being leveraged for SLS Advanced Booster concept development. Using state-of-the-art techniques such as structured light scanning and 3-D printing to translate an existing F-1 engine into a full-fidelity CAD model, Marshall's liquid propulsion experts are examining ways to build on the significant investment of the Apollo Program to reduce costs and improve performance of the SLS.

Space Shuttle — The Center led the design of the Space Shuttle Main Engine (RS-25), which achieved a demonstrated reliability exceeding 0.9996 over 135 missions. Through 30 years of block upgrades and design refinements, the RS-25 continued to incorporate technological advances and improved manufacturing techniques to increase affordability, reliability, and operability. That process of continual improvement continues to pay off today, as the RS-25 is being prepared by Marshall for use in the SLS core stage.

Chandra X-ray Observatory — The Marshall-managed Inertial Upper Stage (IUS) system was used in launching a number of flagship-class science missions during the shuttle era, including Magellan, Galileo, and Ulysses. Marshall led the effort to determine how to boost the Chandra X-ray Observatory — at the time one of the largest and heaviest payloads ever flown — from a shuttle cargo bay to an orbit 87,000 miles above Earth. The IUS was only capable of placing Chandra in a 37,000-mile orbit, so Marshall was tasked with designing an in-space propulsion system to reach the additional 50,000 miles. The resulting dual-mode liquid propulsion system worked in tandem with the IUS to reach the required orbit, delivering groundbreaking data that revolutionized X-ray astronomy. Marshall continues to develop in-space propulsion systems for future science and exploration missions, collaborating with other NASA centers, industry partners, and government agencies.

Constellation Program — In another example of drawing from the lessons of the Saturn rockets, Marshall engineers undertook the design, development, and testing to upgrade the Saturn upper stage J-2 engine to the J-2X engine for use on the upper stages of both planned Ares launch vehicles. Improvements in manufacturing and materials technologies, combined with decades of additional lessons learned about liquid propulsion systems, have been leveraged to design a J-2X engine that will be more reliable and more affordable than its Apollo precursor. With the change from the Constellation Program to SLS, the Marshall SLS Liquid Engines Office continues testing the J-2X at Stennis Space Center as a candidate for powering an SLS Upper Stage.

Marshall's improvements to Chandra's IUS provided the performance boost necessary for revolutionary scientific returns.

	Launch Propulsion Systems	High-Performance Departure Stages	Nuclear Cryogenic Propulsion Stage	High-Performance Descent/ Ascent Propulsion	Robotic, SM, Sample Return, Other Transportation	Satellite, Spacecraft, Small Satellite Systems
Liquid Engine Design	■	■	■	■		
Main Propulsion Systems	■	■	■	■	■	
In-Space Propulsion Systems		■	■	■	■	■
Turbomachinery	■	■	■	■		
Combustion Devices	■	■		■	■	■
Valves, Actuators, and Ducts	■	■	■	■	■	■
Thrust Vector Control	■	■	■	■		
Attitude Control Systems	■	■	■	■	■	■
Health and Status Systems	■	■	■	■	■	■
Instability Analysis	■	■	■		■	
Combusting and Unsteady Flow Fluid Dynamics	■	■	■	■	■	■
Propulsion Systems Integration	■	■	■	■	■	■

Space Launch System — Marshall engineers recently assembled and ignited a cluster of subscale thrusters to verify the SLS propulsion elements before creating a full model mockup. The combined subscale elements simulate the intense conditions of the SLS propulsion system. Marshall fabricated the thruster injectors out of Inconel 625 using state-of-the-art selective laser melting (SLM) processes. These injectors were taken from design through fabrication to the test stand for half the cost and in 15 percent of the time required for traditionally fabricated injectors. Marshall continues to develop these advanced tools and techniques to achieve greater affordability in liquid propulsion system development.

Every Liquid Propulsion Discipline In-House

Marshall's expertise in the area of liquid propulsion covers the entire systems life cycle — from early concept development to detailed analysis and design, through full-scale assembly, testing, operation, and mission support. This end-to-end expertise enables engineers to design with an eye toward manufacturing, operations, and sustaining engineering, which results in more cost efficiency thanks to the Center's unique perspective on the long view of a propulsion system's life cycle.

This expertise encompasses every liquid propulsion discipline from engine and spacecraft systems down to components such as lines, valves, turbomachinery, thrust vector control, injectors, nozzles, chambers, gas generators, and cryogenic fluid management. Identifying cost drivers at the component and subsystem level allows designers to rapidly develop and test improvements, reducing overall development time and cost and ensuring reliability of the final flight hardware. Marshall's co-located cross-discipline team also allows for more rapid design cycles of propulsion systems and subsystems, which also lowers development costs. The high degree of collaboration practiced among the Center's propulsion experts and cross-cutting experts in areas like structures, materials, fluid dynamics, and systems engineering also results in fewer design cycles and revisions, saving cost and schedule.

Comprehensive Facilities for Design, Development, Fabrication, and Testing

Marshall maintains a comprehensive array of facilities that help engineers devise, fabricate, and test liquid propulsion technologies and concepts. These facilities include component manufacturing, performance characterization, and testing, allowing engineers to more quickly move from design to fabrication of test articles and then from the testing and analysis of those articles to design revisions to address any performance issues. This ability to move rapidly through design cycles to arrive at optimized solutions leads to more cost-effective investment of development dollars.

The facilities available to the liquid propulsion engineers at Marshall enable testing of components, subsystems, subscale motors, and full-scale engines under a variety of configurations and conditions. The test engineers in this area have supported many prior NASA programs, including Saturn, space shuttle, and technology development engines such as Fastrac, and are continuing to support development of the SLS propulsion systems design.

The RS-25 Engine: the Evolution of the Highest-Performing Engine Ever Built

The RS-25 engine, most recently seeing service as the Space Shuttle Main Engine (SSME), is the most reliable and highly tested large rocket engine ever built. Throughout the Shuttle Program, Marshall was responsible for the SSME's development, testing, and operation. As industry partners emerged, disappeared, and consolidated over the life of the program, the Center provided a consistency of purpose and design to ensure the engine's unparalleled reliability. During the 30-year space shuttle era, the RS-25 achieved 100 percent flight success with a demonstrated reliability exceeding 99.9 percent. During 135 missions and related engine testing, the RS-25 system accumulated more than 1 million seconds of hot-fire experience.

Improvement of the RS-25 was continuous during the shuttle era. Upgrades were made to the combustion chamber, turbopumps, injectors, and even weld processes to improve the engine's performance and increase its reliability, while simultaneously reducing the required maintenance efforts between missions to lower costs. In addition to the continual efforts to improve upon the RS-25 design, Marshall provided all the necessary sustaining engineering support for the engines and associated propulsion subsystems to the Space Shuttle Program throughout the operational life of the shuttle.

That heritage gave Marshall confidence in selecting available RS-25 engines for the core propulsion of SLS. Under the continued direction of Marshall's SLS Liquid Engines Office, the remaining RS-25 inventory held over from the space shuttle are being prepared to serve as the main propulsion component of the SLS core stage. The RS-25 inventory — the equivalent of 16 engines — represents over $1 billion in assets, thus contributing to SLS affordability. Its proven performance will also contribute to SLS safety and sustainability.

Marshall will leverage $1 billion in existing RS-25 assets to reduce costs for SLS core stage propulsion.

Propulsion Industrial Base Sustainment

Preserving the Nation's Critical Propulsion Capabilities

In a budget-challenged federal environment and an era of increasing industry consolidation, there is an urgent need to integrate across government requirements and to sustain the critical national capabilities in rocket propulsion, research, development, and manufacturing. Marshall has decades of experience working with other government agencies and industry partners to study these capabilities and coordinate efforts to keep the industry moving forward. Erosion of the propulsion industrial base would seriously impact U.S. defense capabilities, space exploration potential, and economic health.

Marshall has led efforts to bring stakeholders together to work these issues, contributed technical expertise to key studies and review boards, and consistently participated in interagency working groups to address propulsion issues.

Collaborating To Identify Challenges and Facilitate Solutions

The center continues to serve as a resource for collaboration and integration among all sectors of the rocket propulsion community. Most recently, Marshall embraced the challenge of preserving and strengthening U.S. leadership in rocket propulsion by inviting government, industry, and academic partners to form the National Institute for Rocket Propulsion Systems. Marshall and these partners examined existing studies and identified "grand challenges" facing the industrial base. The team's work supports policy analyses, identifies technology requirements, and offers options to make best use of national resources to meet future needs. Among its many efforts, this Marshall-led team:

- Led an interagency task team responding to a congressional requirement and the Office of Science and Technology (OSTP) tasking to support development of a National Rocket Propulsion Strategy

At-A-Glance

Rocket propulsion is an enabling technology for our nation's way of life. The technologies that have been developed to support propulsion are critical to national defense, intelligence gathering, communications, weather forecasting, navigation, communications, entertainment, land use, Earth observation, scientific exploration, and many other endeavors. The rocket propulsion industry is also a source of high-quality jobs. Marshall Space Flight Center has continually embraced the challenge of preserving and strengthening U.S. leadership in rocket propulsion by its participation in industry forums and collaboration with other government agencies.

- Facilitated a coordinated purchase of ammonium perchlorate propellant used by every armed service and many commercial firms to stabilize demand for this solid propellant and provide significant cost savings to all government buyers
- Collaborated with the Chemical Propulsion Information Analysis Center at Johns Hopkins University to develop the Cross-Community Skills and Capabilities Directory, which allows propulsion partners and potential customers to easily locate specific propulsion expertise, capabilities, and facilities across the U.S. government
- Developed supply chain analysis methods to support the Space Launch System (SLS) architecture decisions and determine impacts of those decisions on the industrial base
- Developed a survey for Industrial Base Health Metrics
- Performed an OSTP study on national altitude test capability
- Worked with the Air Force Research Laboratory to integrate NASA technology roadmaps with Air Force Integrated High-Payoff Rocket Propulsion Technology roadmaps
- Developed strategies for easier access to government facilities and expertise in partnership with the Defense Acquisition University

Marshall works with multiple government, industry, and academic partners across the country to provide comprehensive factual information to both the propulsion development community at large and policymakers about all issues affecting the U.S. propulsion industry. The center collaborates with those partners to identify solutions to problems both technical and programmatic as they emerge.

As part of the Joint Army, Navy, NASA, and Air Force (JANNAF) interagency propulsion committee, Marshall has participated in numerous subcommittees on all aspects of propulsion technology development. The JANNAF executive committee, consisting of two representatives from each member agency, has included a representative from Marshall since its inception in 1969. The Center has also had numerous executive committee chairs during that time. Through its participation in JANNAF and its subcommittees, Marshall has consistently provided its technical expertise in an advisory capacity to those making decisions about the nation's investment in propulsion technology development and adoption.

As a leader in propulsion development, Marshall has also consistently participated in professional organizations' forums regarding aerospace engineering, particularly in the area of propulsion systems development. Engineers, scientists, and program/project managers from the Center routinely provide papers to trade journals and conferences such as the The American Institute of Aeronautics and Astronautics (AIAA) Joint Propulsion Conference, JANNAF conferences, the Institute of Electrical and Electronics Engineers (IEEE) Vehicle Power and Propulsion Conferences, and the International Aeronautical Congress. This collaboration and exchange of ideas with the broad community of aerospace and propulsion development provides Marshall with the necessary situational awareness to advise the Agency and the nation on investments and partnerships with the propulsion industrial base.

The rocket propulsion industrial base is a crucial capability to the United States for national security, scientific research, human exploration, and economic growth and development. Yet many challenges are now facing that base, including decades of industry mergers and consolidations, the end of the Space Shuttle Program, declining federal budgets, and international competition. At the same time, the emergence of new commercial capabilities offers new opportunities. Marshall continues to offer its unique expertise, insight, and experience to government and industry partners to ensure that this capability remains healthy for future scientific and exploration missions.

Solid Propulsion Technology and Development

Proven Technology for a New Era of Applications

A new generation of technologies is expanding solid propulsion capabilities and increasing their relevance for nanolaunch, in-space, and destination capabilities. Solid propulsion systems continue to be a reliable way to provide thrust and are used in almost every Earth-to-orbit launch capability. Marshall's solid propulsion team has decades of comprehensive experience with solids from nanoscale to heavy-lift applications.

The Center has built a collaborative, scalable, and reliable capability to work with NASA, DOD, and industry to solve future solid propulsion problems.

Marshall continues to mature solid propulsion technologies, including some with breakthrough potential. While supporting ongoing solid propulsion applications for the Space Launch System (SLS) and Orion, Marshall is actively engaged in new development efforts including nanolaunch, low-cost sounding rockets, extinguishable/restartable propellants, and sample return/ascent technologies. Marshall helps lead the way in developing solutions and advancing solid propulsion technologies.

At-A-Glance

Solid propellants are a highly reliable method for delivering thrust and have a wide range of future applicability. Marshall Space Flight Center has comprehensive expertise and extensive experience with solid propulsion for nanoscale to heavy-lift applications. The Center has built a collaborative, customizable, and reliable development capability to work with the solid propulsion community, both to provide design solutions and to mature technology.

Marshall tested a small solid rocket motor designed to mimic NASA's SLS booster. The test provided an effective way to evaluate a new nozzle insulation material.

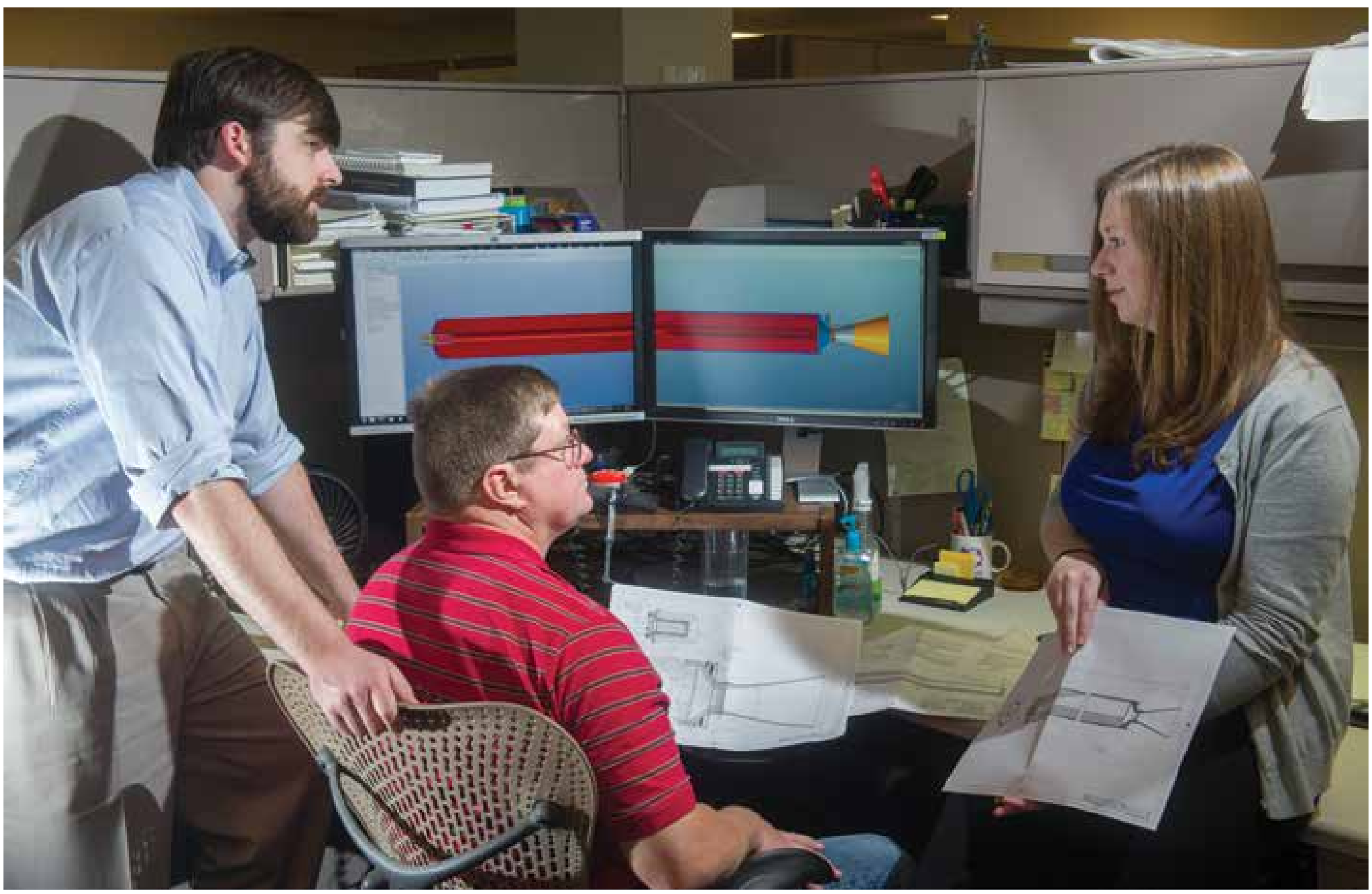
Peregrine — A Solid Solution for Next Generation Sounding Rockets

The Marshall solid propulsion team is demonstrating successful development capabilities, collaboration, and customization expertise with the Peregrine motor development project — a joint project among Marshall, Goddard/Wallops Flight Facility, and industry. NASA's Science Mission Directorate supported the Peregrine development project as a purpose-built sounding rocket sustainer motor using an approach where the government collaborates with industry to generate a build-to-print system that can be produced by multiple vendors.

The Agency initiated Peregrine when a long-term sounding rocket motor, used by NASA and other agencies, developed instability issues. Wallops approached Marshall to lead the development of Peregrine.

All design work, analyses, and materials identification were done at the Center. Marshall worked with the customer's sounding rocket program to identify requirements and is now collaborating with suppliers to produce the motor. Peregrine demonstrates Marshall's range of technical capabilities and ability to collaborate successfully with others.

Through the Peregrine project, multiple NASA centers are working together with industry to realize an economical, reliable solution. Rather than being dependent on a single supplier, NASA benefits by owning a design it can specify to industry for manufacture.



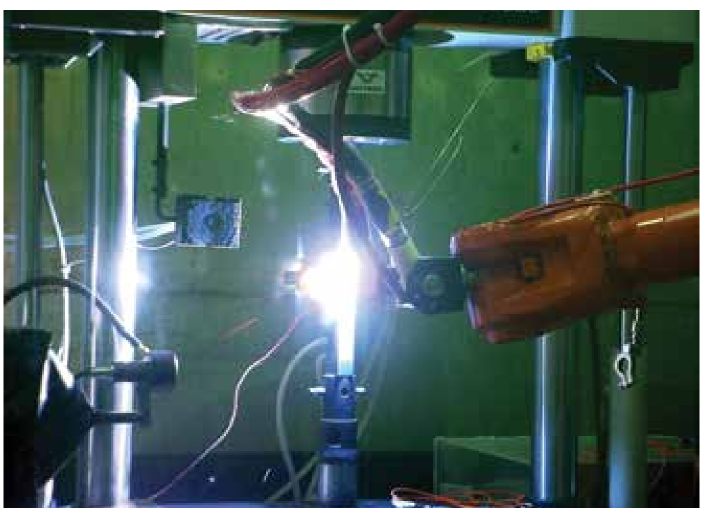
Marshall is collaborating with Wallops to develop the Peregrine sounding rocket motor.

Lead NASA Center for Design, Analysis, Test

Marshall, the hub of solids, is the recognized NASA center for solid propulsion development. The Center has a long history of solid motor development expertise with decades of experience in technical design, analysis, and testing of solids. Marshall's experience extends beyond motors and propellants to the associated technologies necessary for solid propulsion, including igniters, casings, and liner materials for use in solid rocket motors of any size.

Solid Rocket Motor Performance Prediction software is widely used to understand the ballistics (internal flow) of a solid motor. Marshall maintains current software versions — an important capability for both ballistic design and analysis. Thermal analysis is another Center capability that is key to good motor design and analysis. Marshall has world-renowned experts who helped produce the best available software in this field. Structural analysis and computational fluid dynamics are also key capabilities. Marshall can analyze combustion stability and internal acoustics to determine design weaknesses.

Marshall performs tensile tests, mechanical property testing, chemical analysis, and sophisticated chemical species analysis. The Center's Plasma Torch Testing Facility provides inexpensive verification of thermal properties. Additional capabilities include fracture mechanics, nondestructive evaluation, CT-scan and conventional X-ray, and ultrasonic scan. These testing skills also qualify us to perform mishap evaluations. Marshall is the only NASA facility that can test fire solid rocket motors from small to mid-size.



Thermal properties are tested at Marshall's Plasma Torch Test facility.

Close Collaboration with Industry and Government Partners

The Marshall solid propulsion team has world-renowned expertise in solids from small separation motors to heavy-lift applications, and has built a collaborative, customizable, and reliable development capability to work with industry teams to solve problems. This team has a fundamental development capability and conducts research in state-of-the-art technology. Marshall's solid propulsion team has close ties with the solid propulsion industrial base through its long history of operational programs. Marshall is actively engaged in national policy and program forums addressing solid propulsion industrial base sustainment and procurement efficiencies.

A unique facility partnership with the Army Aviation and Missile Research Development and Engineering Center (AMRDEC) makes Marshall the only center that can design, manufacture, and test large motors. The Agency and taxpayers benefit from Marshall's partnership with the onsite Army manufacturing facility to allow casting and mixing of energetic propellants.

Advanced Development and Future Mission Applications

Marshall has extensive experience with in-space motors that propel scientific payloads into the correct trajectories. Marshall's solid propulsion experts are collaborating with the Solar Probe Plus (SPP) third stage motor supplier in the development process and supporting NASA's Independent Program Assessment Office in their assessment of SPP.

Marshall is actively engaged in future mission applications including nano-launch, low-cost sounding rockets, sample return/ascent technologies, printable rockets, and extinguishable, restartable propellants. Currently, Marshall is working with industry to explore a new propellant technology that can be ignited, extinguished, and re-ignited multiple times by applying and removing an electrical current. This extinguishable solid propellant technology could be used on small in-space propulsion projects, allowing these small satellites to benefit from the high volumetric efficiency of solid propellants. Recent research has also explored improving the efficiency of propellant mixes, and Marshall is currently testing propellants for exposure to simulated Mars environments in support of future sample return mission concepts.

Marshall's work on booster separation motors for the Space Launch System and the Launch Abort System for Orion illustrates the Center's ability to scale its solid propulsion capabilities to any spacecraft size or mission need. In addition, Marshall's expertise extends from initial design to manufacturing oversight, testing, and operational support.

The successful test firing of the Orion jettison motor is the first full-scale rocket propulsion element qualified to proceed into a system-level demonstration.

Structural and Propulsion Test

Testing Affordably and Accurately at Any Life-cycle Phase

Affordable development of new launch and propulsion capabilities places a premium on maximizing the return on critical ground tests. Tests must yield high-quality results both in data and subsequent analysis, fit into aggressive development schedules, and allow developers to minimize costly test-fail-fix cycles. Marshall engineers have unique experience with rapid design of tests, work closely with customers to customize and design right-sized tests, and have deep engineering disciplinary reach-back capability to provide rigorous analysis and interpretation of test results.

Marshall's broad capabilities in structures and propulsion have been critical to many of the Agency's programs, including Saturn, Skylab, Space Shuttle, and the International Space Station, as well as numerous technology development projects. These capabilities include testing of liquid or solid propulsion systems as well as structures for launch vehicles and spacecraft of all sizes, in-space structures, and associated support hardware through experimental, developmental, or operational life-cycle phases. Marshall's structural and propulsion testing capabilities continue to serve a vital role in support of the Space Launch System (SLS), Orion crew vehicle, NASA's commercial crew and cargo programs, and technology developments to make future missions safer and more affordable.

At-A-Glance

Launch vehicle and related propulsion system development, constrained by limited government budgets or cost-sensitive commercial pressures, requires the right test in the right amount of time. Marshall Space Flight Center maintains unique national test facilities and deep experience in the discipline of test engineering to support development efforts through customized test programs.

Early component testing of propulsion systems reduces technical and programmatic risk.

Comprehensive Facilities for Any Test Program

At all phases of design, development, test, and operations, projects need the ability to simulate conditions where the hardware operates. Short of actual flight, this can only be accomplished with custom-built test articles using a range of facilities that produce specific conditions. Engineers can then integrate the results of such tests into a more comprehensive understanding of what should happen, or did happen, from start to finish. Marshall has executed test programs like this for complete vehicles including Saturn and space shuttle, industry partnerships such as the RD-180, and technology development efforts such as FASTRAC.

Marshall houses a comprehensive set of testing facilities for propulsion and structural systems, as well as cross-cutting environmental testing facilities. In order to develop both test articles and custom-designed test fixtures and adapters, the Center also has a full range of supporting capabilities, including machine shops, test support and logistics services to supply consumables and instrumentation, and test planning support for budget analysis and risk management of test programs.

Propulsion testing facilities at Marshall enable testing of components, subsystems, subscale motors, and full-scale engines under a variety of configurations and conditions. The test engineers in this area have supported many prior NASA programs and continue to support development of the SLS propulsion systems design. Some notable facilities in support of this testing capability include:

- Test Stands 115, 116, 500, and multiple smaller test cells, which provide the ability to test injectors, preburners, turbopumps, combustion chambers, igniters, seals, bearings, valves, engine subsystems, small solids, and vehicle acoustic modeling with minimal facility modification
- The Hydrogen Cold Flow Facility, which provides safe, inexpensive, low-pressure flow tests of hydrogen engine and subsystem components
- The Hot Gas Test Facility, which generates flow speeds up to Mach 4 and high heating rates to test materials and coatings. The Hyperthermal Test Facility can test smaller samples to much higher heating rates, including environmentally safer solid motor liner materials.
- The Solid Propulsion Test Facility, which simulates solid rocket motor combustion environments, and can test fire solids vertically or horizontally
- The Advanced Engine Test Facility, which is a two-position, tri-propellant stand capable of evaluating full-scale engine and vehicle stage systems

Test stands such as TS500 can be quickly configured to test an array of propulsion components.

Developing Test Programs for Propulsion Systems Structures

Marshall's test expertise extends beyond individual tests conducted on components, subsystems, propulsion systems, or structures. The Center's structural and propulsion testing team is capable of designing comprehensive test programs to take projects and programs from the early subscale component tests through full-scale testing of flight-like hardware.

Collaborating with customers to develop a test regime of appropriate complexity and rigor for each project, the Center provides a consistent and methodical approach to test programs that drives down technical risk by moving developmental hardware through a series of tests, testing individual components before integrating them into subsystems, testing those subsystems, and proceeding to final hardware configurations. Decades of experience in this kind of testing enable Marshall to execute this thorough testing rapidly, using the range of configurable facilities on site.

J-2X

NASA's Constellation program originally resurrected the Apollo-era J-2 engine to serve as upper stage propulsion for the Ares launch vehicles. In order to meet mission requirements, performance needed to be improved and on-orbit restart capabilities added. The resulting J-2X engine development program began immediately on a comprehensive update of the original engine with the latest in liquid propulsion technologies, materials, and techniques.

A critical part of the updates to the J-2X was a thorough test program to identify optimal configurations of the engine's many subsystems and components, beginning with multi-element injector testing, subscale gas generator tests, and power-pack testing. As Constellation efforts were transitioned to the Space Launch System, J-2X continued forging ahead with its test program, moving to full-scale engine hot-fire testing and advanced testing of a regenerative engine nozzle to improve performance.

Marshall continues testing J-2X components and subsystems to incorporate the latest materials and manufacturing technology improvements. The Center recently conducted a hot-fire test using a 3-D printed injector plate for potential use in J-2X. A series of such tests will determine the optimal configuration of injector elements to maximize performance while minimizing mass.

Shell Buckling

As part of any launch vehicle design process, structural test articles are frequently assessed to determine how to obtain the required structural strength with the lowest possible mass. The Shell Buckling Knockdown Factor (SBKF) test project is examining the safety margins needed in the design of future large launch vehicle structures. Research to date suggests a potential weight savings of as much as 20 percent. As this test program continues, the results will be used to develop and validate structural analysis models and generate new shell buckling knockdown factors — complex engineering design standards essential to launch vehicle design.

In order to ensure the performance of core stage and upper stage structures, the test team receives completed barrel sections, assembled on site using Marshall's large-scale manufacturing capabilities, and tests these barrel sections to failure using compression. To date, numerous subscale articles, a variety of orthogrid structural patterns, have been tested to optimize the structural design and minimize mass. In addition, full-scale "can crusher" tests have occurred to test full-scale structural barrels and verify that they can meet the extreme requirements of a launch vehicle ascent.

A shell buckling test article helps vehicle designers optimize mass and meet structural requirements.

Thrust structures, propellant tanks, and other components require equally demanding and precise testing, often to destruction, to ensure adequate safety margins for flight vehicles while minimizing the mass of those structures. Marshall facilities can apply millions of pounds of mechanical loads in compression, tension, and laterally, and apply environmental profiles such as heat, cold, vacuum, and humidity to test articles. Multiple facilities, high bays, and reaction floors provide proof, limit, failure, development, qualification, or flight acceptance levels and environments of testing. Notable facilities in support of structural testing include:

- The Cryostructural Test Facility, which evaluates the structural integrity of tanks and other propulsion components under compression, sheer, and tension loads
- The TS 300 Environmental Test Facility, which simulates ascent launch profiles and deep space vacuum for cryogenic fluid management
- Marshall's Large Structural Test Facilities, which can accommodate test articles up to 33 feet in diameter and apply 30 million pounds of strain vertically and 2.4 million pounds laterally, and also accommodates cryogenic temperatures, heating, and acoustics

In addition to the extensive facilities for performing structural and propulsion tests, Marshall has decades of experience with developing instrumentation for structural and propulsion test articles to create maximum data return. High-speed data acquisition, visible and thermal imaging at more than 18,000 frames per second, and high-definition audiovisual capture systems allow test engineers to instrument a customer's test article with all the necessary systems to provide exactly the data that the designers need to evaluate and characterize their systems, whether early proof-of-concept articles or flight-qualification of integrated systems.

Advanced Propulsion Technology and Development

Innovation To Explore

Many advanced propulsion technologies are currently at medium technology readiness level, but opportunities for ground or in-space demonstration are limited. Crossing this technology development "valley of death" affordably is key to bringing these technologies online to serve future exploration needs. For current and near-term propulsion needs, the Center is advancing technologies for cryogenic fluid management (CFM) for in-space propulsion as well as testing new green propellants. For long-term exploration needs, Marshall provides technical risk reduction by advancing a range of technologies to provide affordable, efficient propulsion that enable new mission concepts, including nuclear thermal propulsion, electric propulsion, satellite tethers, and solar sails.

At-A-Glance

Today's in-space propulsion challenges are focused on chemical propulsion, while tomorrow's missions will require advancing the state-of-the-art of propulsion system performance through nonchemical systems. Marshall Space Flight Center has unique experience in many of these areas and the capabilities to rapidly prototype, test, and integrate new propulsion system concepts.

Marshall evaluates a subscale composite cryotank to advance TRL prior to full-scale testing.

Enhancing Today

Marshall's research into CFM includes the storage, fluid distribution, liquid acquisition, and mass gauging of cryogenic propellants. These tasks reduce the development risk and increase the technology readiness of advanced CFM subsystems to store and distribute cryogenic propellants required for long-term exploration missions. CFM utilizes the development of prototype CFM hardware, the creation and use of analytical models to predict sub system performance, and the execution of ground-based tests using liquid oxygen, liquid hydrogen, and methane to demonstrate the performance, applicability, and reliability of CFM subsystems.

Several testbeds support cryogenic propellant storage and transfer research, including the large-scale 10-foot Multi-Purpose Hydrogen Testbed; the 6-foot Cryogenic Test Bed tanks for liquid oxygen damper testing; the 4-foot vibroacoustic tank; and three small-scale stainless steel tanks, one 3-foot and two 18-inch. The tanks can be used for vacuum testing and can run autonomously around the clock.

Marshall is also developing new cryogenic propellant tanks using composite materials, which could provide a substantial mass and cost savings, enabling future missions to reach new destinations. Working with an industry partner, subscale test articles have undergone pressure testing, and a full-scale test article is in development for continued technology development and testing.

The Center also supports the Agency's efforts to develop green propellants for future chemical propulsion systems — propellants less toxic or environmentally hazardous than existing propellants like hydrazine. Working with industry partners, other NASA centers, and interested government agencies, Marshall conducts research and characterization of a variety of candidate propellants to reduce technical risk for ongoing advanced propulsion development efforts and offers testbed capabilities to assess a variety of propellants.

Enabling Tomorrow

Opening the solar system for human exploration will require maturation of nonchemical space propulsion. NASA's current design reference for a human mission to Mars has options for nuclear thermal propulsion and electric propulsion for reaching the destination. In the years leading up to a human planetary mission, these advanced propulsion concepts can also improve robotic precursor missions. Other propulsion technologies, including tethers and solar sails, have applications for both near-Earth and deep space exploration with unmanned spacecraft.

Marshall operates two facilities for nuclear thermal propulsion research and testing. The larger of these, the Nuclear Thermal Rocket Element Environmental Simulator (NTREES), performs realistic non-nuclear testing of various materials for nuclear thermal rocket fuel elements. The NTREES facility is designed to test fuel elements and materials in hot flowing hydrogen, reaching pressures up to 1,000 psi and temperatures of ~5,000 F to simulate space-based nuclear propulsion systems and provide baseline data critical for risk reduction in future propulsion development. The Compact Fuel Element Environmental Test (CFEET), which conducts high-temperature, but not high-pressure, testing, is licensed to test with depleted uranium. By combining our foundational and applied nuclear and materials research and expertise, Marshall provides a unique capability to conduct the entire research process in-house, from design and development of fuel elements to testing.

In the area of advanced fusion research, Marshall is a partner with the University of Alabama at Huntsville's fusion pulse power research project, along with Boeing and the STMD. The research utilizes a donated DOD apparatus originally used for research into nuclear weapon effects. The full assembly weighs almost 50 tons and provides nearly 500,000 joules of energy per pulse.

Electric propulsion research includes unique capabilities in high-power pulse-electric propulsion systems and nuclear fusion propulsion research. Supporting electric propulsion research, Marshall operates a low-thrust vacuum chamber, which also can be used for chemical propulsion research. A recent test successfully simulated a 6-pound thruster using residual propellants from a spent upper stage. As a result, the industry partner can consider adding such thrusters for satellite attitude control or as a means of de-orbiting spent stages. The chamber can test other novel propulsion concepts such as hybrid solid/electric systems.

Marshall has also managed four of NASA's tethered satellite experiments, the Shuttle Tethered Satellite System (TSS-1 and -1R) and the Small Expendable Deployer Systems (SEDS I and SEDS II). Tethers have great potential for raising satellites or deorbiting them at the end of operations by operating as an electric motor with or against Earth's magnetic field. The Center continues to investigate advanced uses for satellites orbiting beyond 70˚ inclination for Earth observation, weather, telecommunications, remote sensing, and planetary exploration.

The Center has been involved in solar sail research from concept to flight. In 2004, Marshall helped test the strength, stiffness and behavior of two competing designs. These led to NanoSail-D and Sunjammer. NanoSail-D, which Marshall managed in 2010, became NASA's first solar sail to achieve orbit. The 100-square-foot polymer sail demonstrated deployment of a compact solar sail boom technology. Marshall now manages Sunjammer, the largest solar sail technology demonstration mission, set for launch in 2014. At nearly 13,000 square feet, it will also demonstrate debris collection and removal from orbit and de-orbit of spent satellites. Potential solar sail missions include polar-stationary Earth observations, heliophysics, NEO reconnaissance, interstellar precursors, orbital debris mitigation and small satellite propulsion.

NanSail-D served as a proof-of-concept for deployable solar sail technologies.

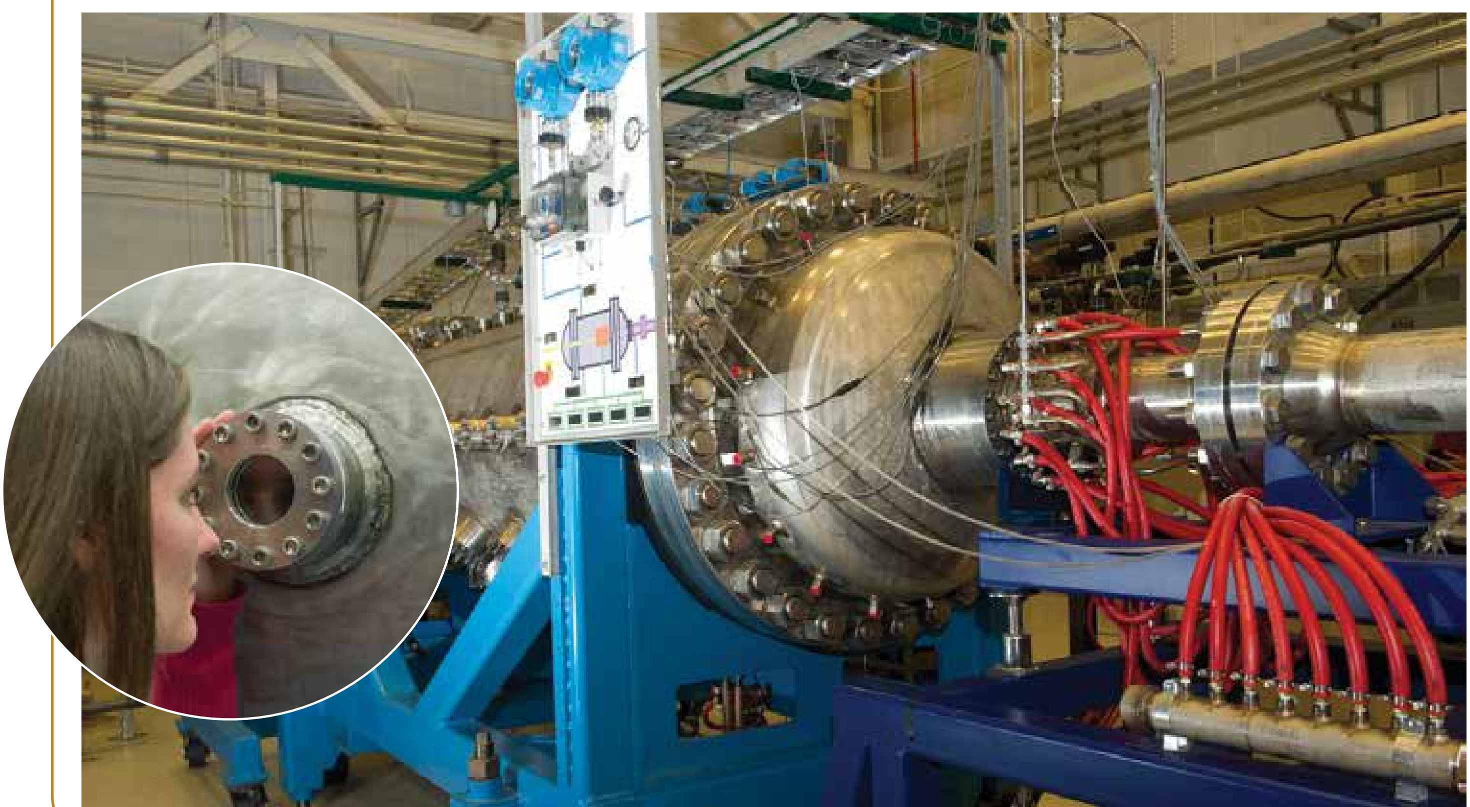
From Nuclear Technology to In-Space Stage

The Nuclear Cryogenic Propulsion Stage project, led by Marshall for the Advanced Exploration Systems program, includes participation by the Department of Energy. The program focuses on crew safety and mission operations in deep space to enable new approaches for rapidly developing prototype systems, demonstrating key capabilities and validating operational concepts for future vehicle development and human missions beyond Earth orbit.

The team is engaged in a three-year project to demonstrate the viability of nuclear propulsion system technologies. The design uses a nuclear reactor to super-heat hydrogen, which expands through a nozzle to generate thrust. A first-generation nuclear cryogenic propulsion system could propel human explorers to Mars more efficiently than conventional spacecraft, reducing crew exposure to harmful space radiation and other effects of long-term space missions. It could also transport heavy cargo and science payloads. Further development and use of a first-generation nuclear system could also provide the foundation for developing extremely advanced propulsion technologies and systems in the future — ones that could take crews even farther into the solar system.

Building on previous successful research and using the NTREES facility, Marshall can safely and thoroughly test simulated nuclear fuel elements of various sizes, providing important test data to reduce technical risk in the design of the Nuclear Cryogenic Propulsion Stage.

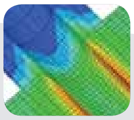
NTREES conducts risk-reduction tests on fuel-simulated nuclear fuel elements.



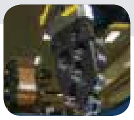
Marshall Space Flight Center

Materials and Manufacturing

Materials and Manufacturing

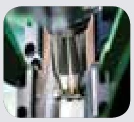


- Materials Diagnostics and Fracture/Failure Analysis



- Materials Technology and Development

- Advanced Manufacturing



- Large-Scale Manufacturing

Materials Diagnostics and Fracture/Failure Analysis

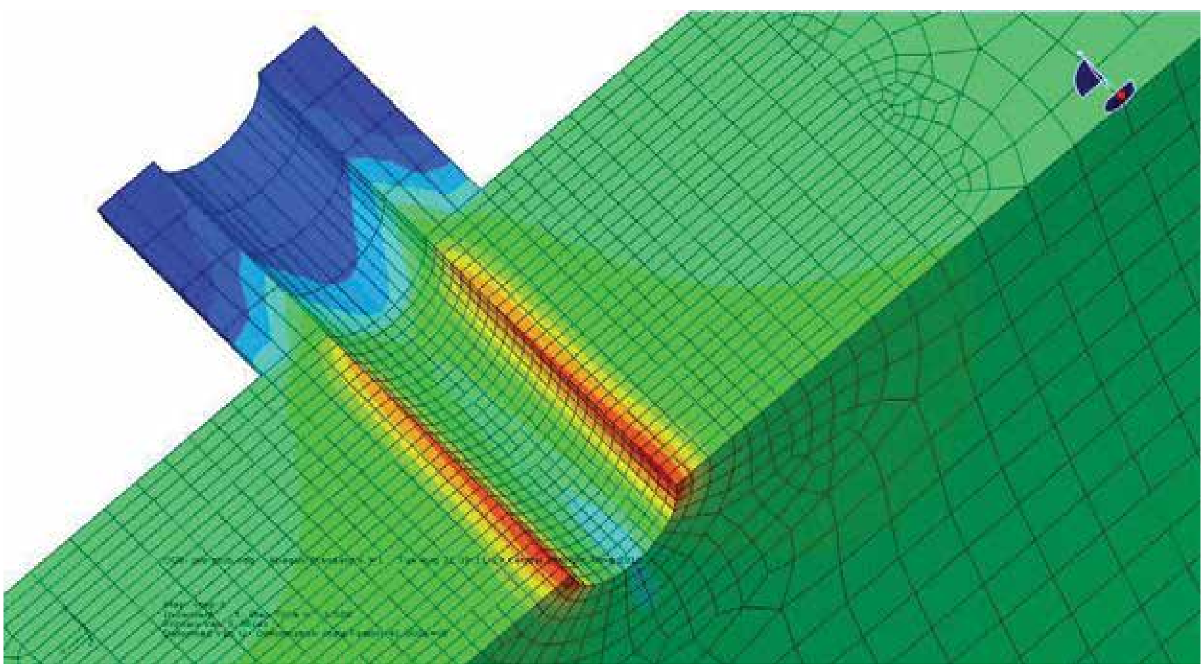
Ensuring Mission Safety and Advancing Space System Manufacturing

Preparing for missions in space requires continually incorporating new materials and processes that enable delivery of cutting-edge design solutions and yet still meet stringent safety requirements for crewed systems. Marshall quickly and thoroughly identifies materials performance and failure issues, advancing the state of the art in space system manufacturing and testing and leading to safer space solutions to meet Agency needs.

Marshall's materials diagnostics, damage tolerance, and failure analysis capabilities ensure crew safety and mission success throughout the service life of spaceflight vehicles, habitation modules, and propulsion systems. This extends down to the component and subcomponent level, including core materials, coatings, and hardware, as well as the manufacturing processes to deliver them. The Center has a proven track record as a leader in safely, routinely delivering sound, reliable launch vehicles, spacecraft, and hardware — from manufacturing to low Earth orbit and beyond.

At-A-Glance

Space applications require continual incorporation of new materials and processes to identify the lowest cost and lowest mass solutions. Advancing design while meeting safety requirements requires an expert team that can identify material performance and failure issues quickly and comprehensively. By continually advancing the state of the art in materials diagnostics and failure analysis, Marshall Space Flight Center is helping to advance the state of the art in space system manufacturing leading to safer, more affordable solutions.



Marshall's state-of-the-art diagnostics ensure safe, affordable design solutions.

Keen Analysis, Expert Diagnostics

Historically founded in quality assurance during the Apollo Program and continuously evolving with advancing technology, Marshall's materials diagnostics, damage tolerance, and failure analysis capabilities are vital to NASA's mission. Marshall experts pursue an interconnected series of specialties in these fields — adding up to a national resource for this complex and critical activity. Marshall has unique expertise and in-house knowledge to correlate advanced fracture analysis with hardware tests, as well as a full complement of non-destructive evaluation (NDE) techniques, technologies, and test facilities.

Marshall has much experience in conducting damage tolerance testing (fatigue and fracture testing) of critical NASA and industry hardware and processes, proving hardware and materials for space shuttle and supporting development of the latest next-generation vehicles and space systems. The Center experts in crack growth analysis in propulsion systems and large-scale structures worked closely with Boeing to conduct fracture testing on friction stir welds for the Space Launch System (SLS) Core Stage, helped detect the cause of cracked stringers on the STS-133 external tank, and aided Orbital and Aerojet in investigating manufacturing defects and stress corrosion cracking in AJ26 heritage engines.

The Center frequently is called upon by Agency and industry partners to perform custom NDE inspections of hardware and vehicles, including test articles and elements for SLS, next-generation Cryogenic Propellant Storage and Transfer, and International Space Station (ISS) hardware. Marshall also partners with industry, supporting NDE evaluations for ATK, Aerojet Rocketdyne, Blue Origin, Boeing, Dynetics, Lockheed Martin, and other industry partners.

Marshall is a recognized resource for anomaly resolution and failure analysis at any scale, supporting many successful investigations, including examination of Solar Alpha Rotary Joint (SARJ) bearing failure on the ISS and the crash investigation of TWA Flight 800 in 1996.

Together, the damage tolerance, NDE, and failure analysis teams perform a variety of vital root-cause assessment tasks. Key assessments have included:

- Failure analysis of leading-edge composites after the Columbia accident
- Computation of acceptable disbond sizes for a cryogenic tank common bulkhead honeycomb sandwich structure
- Analysis of Space Shuttle External Tank spray-on foam insulation (SOFI) failure mechanisms and debris liberation
- Failure analysis of Apache, Blackhawk, Chinook, and Observation helicopter parts
- Development of phased array ultrasonic testing for friction stir welding and friction stir plug welding
- Investigation of high-cycle fatigue and hydrogen embrittlement effects of Space Shuttle Main Engine (SSME) high-pressure fuel turbopump turbine blades
- Failure analysis and test evaluation of debris liberation estimates supporting STS-126 Shuttle Main Propulsion System flow control valve fracture

Expert Analysis To Ensure Safety and Mission Success

Marshall crack growth analysis experts leverage state-of-the-art technologies, advanced investigative methods, and proven tools and testing standards to develop and implement thorough, precise assessments to mitigate risk due to damage and defects in manufacturing and assembly and throughout the hardware life cycle. They identify defects in materials, discover how defects are formed, and determine how much damage each material can withstand — whether sustained during a launch or in-flight anomaly or accumulated over the course of the life cycle.

To ensure that flight hardware, payloads, and launch vehicles are strong enough to survive the rigors of launch and spaceflight, Marshall analyzes metals and composites to understand each material's ability to withstand the loads and conditions encountered during mission life. Center experts co-chair the Agency's Fracture Control Methodology Panel to ensure uniformity of fracture control standards and requirements across NASA. They also chair the Fracture Control Board at Marshall.

When it becomes necessary to examine intricate, complex pieces of hardware without pulling them apart to see how they survive testing or use, the Non-Destructive Evaluation team conducts in-house analysis of laboratory results for hardware acceptability and flight rationale.

The Failure Analysis team uses tools and techniques to assess and diagnose failures in hardware, coatings, processes, and products, reducing the likelihood of further project/mission setbacks or delays.

World-Class Sites of Innovation

Mechanical Test Facility

Enabling engineers to conduct standard and nonstandard mechanical tests, from elevated to cryogenic temperatures, the Mechanical Test Facility is home to a wide range of customized tests to evaluate stress and fracture issues — including simulated service loads in simulated space environments. Standard tests meet all government and industry specifications.

Hydrogen Test Facility

The Hydrogen Test Facility is a unique national resource, featuring eight structurally reinforced test cells that enable an extensive, customizable range of stress-, pressure-, and temperature-based hydrogen tests. This facility was the first in the world to run high-pressure cryogenic permeability tests in liquid hydrogen at pressures up to 300 psi.

Materials Diagnostics and Failure Analysis Facilities

Highly skilled, highly trained Marshall engineers investigate the underlying, contributing causes of failures in order to minimize operational risk and optimize system reliability. Marshall's Materials Diagnostics and Failure Analysis Facilities maintain a suite of optical, stereo, scanning and transmission microscopes suitable for analyzing metallic, composite, ceramic, biological, and geological samples.

Surface Analysis/Microscale Material Characterization Facilities

Low-voltage/high-resolution electron microscopy, X-ray photoelectron spectroscopy, and secondary ion mass spectroscopy are used by Marshall researchers in the Surface Analysis/Microscale Material Characterization Facilities to perform detailed analysis of thin films and submicroscopic deposits. They also provide detailed data interpretation for individual materials applications.

Non-Destructive Evaluation Facilities

Marshall's Non-Destructive Evaluation Facilities provide critical NDE development, analysis, and inspection capabilities for large-scale structures, propulsion systems, and flight articles using standard and specialized methods and equipment — from radiography, eddy current technology, and magnetic particle inspection methods to phased-array ultrasonics, computer tomography, laser shearography, terahertz, thermography, and microwave methods.

X-ray analysis of materials is one of many methods used at Marshall to reduce risk.

Out of the Past, into the Future

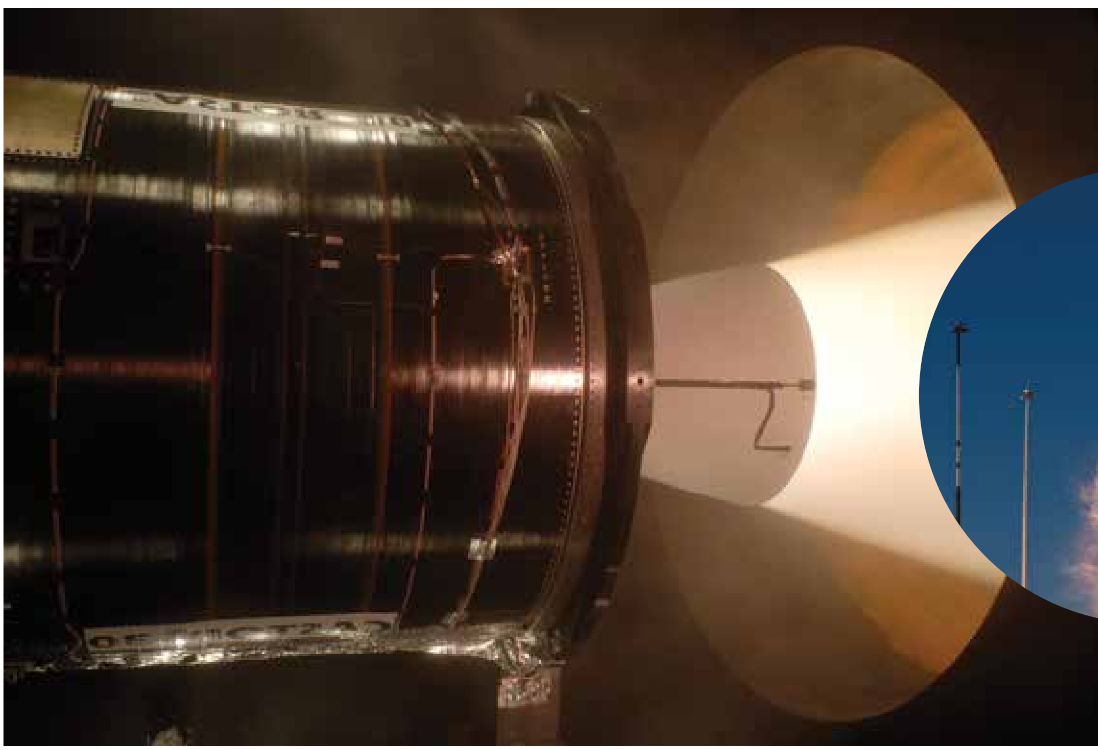
Marshall materials engineers provided critical assistance to Orbital Sciences Corp. and Aerojet in the assessment of structural material capability for the AJ26 liquid rocket engines used on the modern Antares launch vehicle.

The AJ26 engines are slightly modified Russian NK-33 engines built in the early 1970s. Because the engines are heritage Russian hardware, details of the material capabilities are not available, and heritage Russian production processes no longer can be readily replicated — especially for the welds on the engine ducts.

To meet this materials diagnostics challenge, the Marshall team had to determine innovative ways to dissect and test extremely limited amounts of sacrificial engine hardware to determine its capabilities in the presence of stress corrosion cracks.

Given the highly complicated, curved surfaces of the engine hardware, the team devised unique test-specimen designs, test fixturing, test measurements, and nonlinear analysis techniques.

Using Marshall's state-of-the-art facilities and in-house expertise, the team successfully determined the full range of capability of the welded engine material. Now, Orbital and Aerojet are putting the results of that comprehensive testing to practical use — ensuring continued successful operation of the Antares launch vehicle.



Marshall's expert assessment of AJ26 engines helped keep Antares on schedule.

Materials Technology and Development

Optimizing Processes To Speed Design Solutions

In order to ensure the affordability, reliability and strength and minimize the mass of space launch and space system elements, designers must identify and qualify the optimal materials for use, as well as the processes to be applied during manufacturing. The Marshall Space Flight Center excels in identifying and selecting material and process options during design without interrupting or compromising development schedules. Because Marshall is able to develop processes in-house, its materials specialists bring to bear a depth of experience in timely materials selection that is hard to match. Marshall possesses special expertise in composite and lightweight materials, large scale structures and propulsion elements and comprehensive test and process simulation capabilities to further speed the selection process.

As a leader in process development and optimization, Marshall is home to a full-service materials research, development and manufacturing laboratory, including more than a dozen critical test facilities and a complementary suite of tools to evaluate chemical and microstructural characteristics, mechanical and fatigue properties, tribological and corrosion effects, and the influence of extreme temperature and pressure environments. The Center's materials engineers and technologists possess the hands-on experience and cutting-edge expertise to make timely, effective use of these facilities to benefit the work of NASA, its partners and the nation.

At-A-Glance

The experience and expertise of Marshall engineers and technicians enables them to select materials and optimize processes without interrupting work already underway. Any materials selection group will offer an "optimal" solution; Marshall's leaders in materials technology and development offer an optimal solution that fits best with real-world project development needs.

Marshall tests composite materials to enable lightweight design solutions.

Timely Materials Selection To Enhance System Performance

New materials are constantly needed that deliver greater performance, improved cost effectiveness, superior reliability and better safety, while also minimizing environmental impact. Responsible for the selection, development and optimization of materials and advanced processes, the experts at Marshall are critical to ensuring the quality and performance of NASA's space launch and space system elements.

Marshall engineers have special expertise in composite and lightweight materials, propulsion materials and comprehensive test and process simulation capabilities to further speed the selection process. They frequently are called upon by government and industry partners to develop and optimize advanced processes for new aerospace materials. They also design and execute certification programs for the use of specialty alloys and product forms in crewed space hardware design.

Obsolescence Mitigation and the Materials Replacement Program
Obsolescence mitigation is an important aspect of Marshall's materials selection expertise. Environmental regulations, industrial process development, and materials technology advancements all drive new requirements and considerations into the selection of appropriate materials. Leveraging the Center's broad base of material properties and analysis knowledge, new materials can be found quickly to replace those that are unavailable or obsolete without impacting ongoing design cycles or production schedules.

Marshall offers a comprehensive program for replacement of thermal protection system materials that have become obsolete due to loss of suppliers, environmental regulations or changes in the manufacturing process. The program analyzes the impact of a change in materials, develops programs to demonstrate equivalence to prior materials and evaluates the capability and performance of newly developed materials.

Ultrasonic stir welding processes using portable tools will enable in-space fabrication and repairs.

Meeting Production Challenges in Real Time

Proximity to working commercial production lines — and co-location with Marshall's propulsion, structural, thermal and test facilities — enables materials engineers and technicians to work side-by-side with customers, solving real-world production challenges with minimal impact to the manufacturing flow, and delivering practical, timely solutions that meet today's needs and maintain preparedness for tomorrow. These facilities allow the Center to support any facet of materials characterization or ongoing production process analysis, while constantly advancing the state-of-the-art in materials technology and process development.

Advanced Weld Process Development Laboratory
As aerospace materials continue to evolve, sophisticated manufacturing processes must be designed for their use. Specializing in the transfer of advanced joining process from the laboratory to full-scale manufacturing of large, complex structures, this facility provides a range of advanced joining processes including friction stir welding, ultrasonic welding, variable polarity plasma arc welding, tungsten inert gas welding, electron beam welding and brazing.

Ceramic Matrix Composite Development Facility
Working to promote the use of CMC materials for propulsion, structures and thermal protection system needs, this facility has aided in CMC development for the Orion Launch Abort System; carbon-fiber-reinforced carbon for large-liquid engines and winged hypersonic vehicles; and development of advanced ceramic fuel elements for nuclear thermal propulsion.

Cryo-insulation Development Facility
Cryogenic Fluid Management (CFM) technology is an integral part of exploration systems for Earth-to-orbit transportation and crewed missions to the moon and Mars. The Cryo-insulation Development Facility provides the ability to apply primers and spray-on foam insulation (SOFI) materials to large-scale test articles, and maintains capability for cryogenic testing, chemical fingerprinting, robotic and manual foam spray operations, raw materials acceptance and personnel certification.

Subscale Solid Rocket Motor Processing Facility
This facility is used to find alternative materials for solid rocket motor applications that have suffered from material obsolescence issues. Its unique, proven plasma torch test bed (PTTB) enables engineers to evaluate a material's ability to protect against the plume environment and to validate material and process changes before implementation on full-scale motors.

Fifty Years of Cutting-Edge Solutions

Built on proven knowledge and successful delivery of flight-ready vehicles, structures, propulsion systems, and thermal protection systems, Marshall's expertise in materials technology and development constantly is honed, updated and expanded by practical, in-house research and development activities and by partnerships with commercial manufacturers, research institutions and standards organizations.

Fifty years of frontline experience in building complex systems, developing new manufacturing processes and resolving investigative actions has taught Marshall engineers how to deliver cost-effective, real-world solutions to meet the development program's needs.

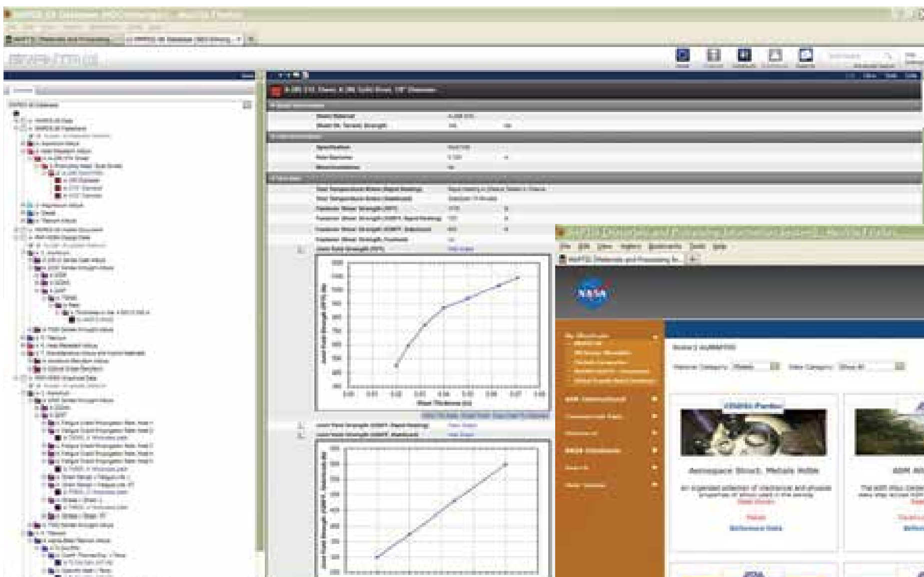
Marshall materials and technology accomplishments include:

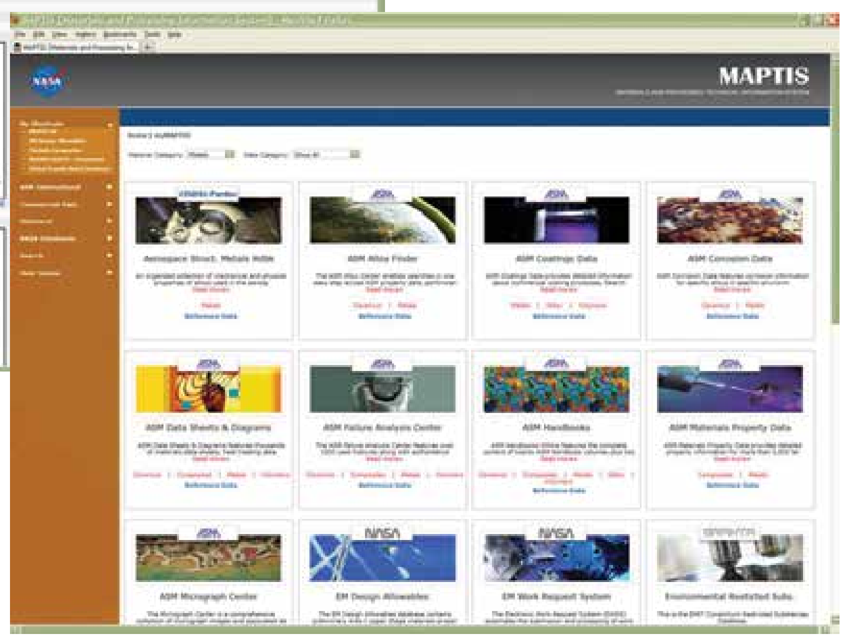
- Development of tooling and weld schedules for the core stage of the Space Launch System
- Fabrication of a 27.5-foot-diameter shell-buckling barrel assembly to validate and update models for launch vehicle core structures
- Development of a novel approach to manufacture large-scale aluminum-lithium spin-formed domes
- Design, development and manufacturing of laser and electron-beam welding techniques to manufacture flight hardware and components of the Environmental Control and Life Support Systems aboard the ISS
- Fabrication of tungsten-based uranium dioxide CERMETs and mixed uranium carbide fuel elements for nuclear thermal propulsion
- Development of cleaners, primers, conversion coatings and anodized surfaces for the replacement of hexavalent chrome containing corrosion protection materials

Unmatched, Accessible Body of Materials Knowledge

Marshall's Materials And Processes Technical Information System (MAPTIS) provides an efficient and reliable means of supplying information needed for the selection and application of materials and processes to produce the hardware required for NASA and industry space missions. This unique resource is used throughout the aerospace community and beyond as a central clearing-house of properties data for more than 32,000 materials, drawn from more than 30+ materials property databases within NASA, DOD and other government agencies, and private industry. This extensive knowledge base furthers Marshall's ability to provide rapid materials selection expertise to Agency programs and external partners.

More than just a catalog of materials and properties, MAPTIS takes advantage of lessons learned from past failures and problems to avoid similar issues in future projects. The materials characterization data also allows projects to forego costly and redundant materials testing. New data is continually added to the system from ongoing material testing and analysis, and existing materials are updated to reflect any environmental, safety, and health classifications that might limit their use in specific applications.





Marshall maintains the most comprehensive database of materials properties in the world.

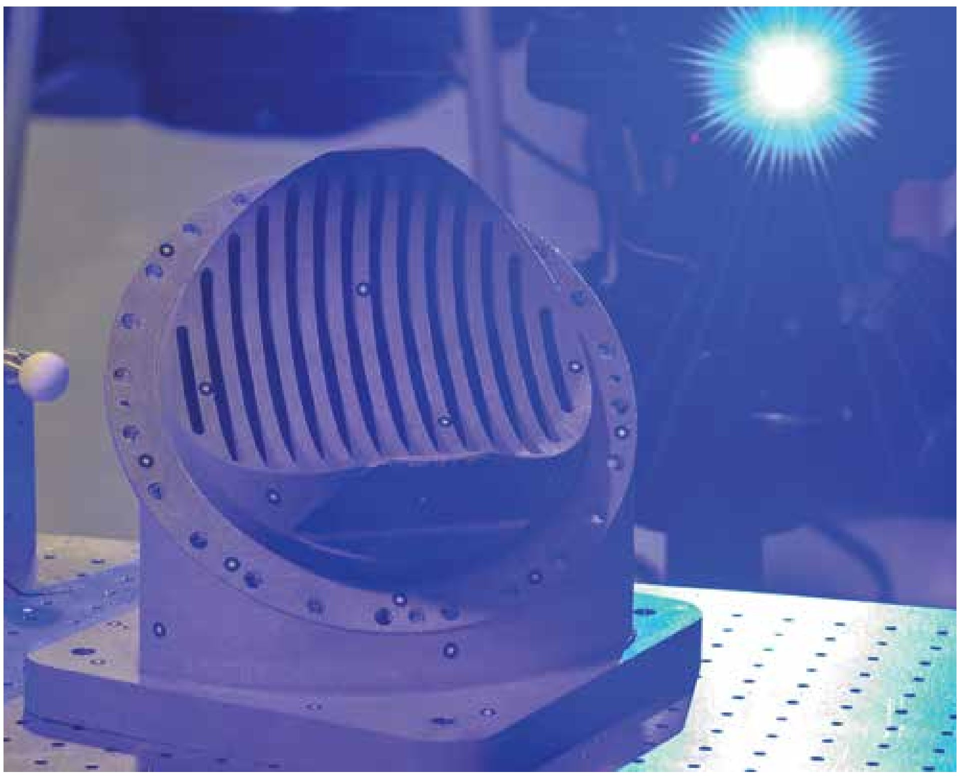
Advanced Manufacturing

Pioneering Affordable Aerospace Manufacturing

Rapidly evolving digital tools, such as additive manufacturing, are the leading edge of a revolution in the design and manufacture of space systems that enables rapid prototyping and reduces production times. Marshall has unique expertise in leveraging new digital tools, 3-D printing, and other advanced manufacturing technologies and applying them to propulsion systems design and other aerospace materials to meet NASA mission and industry needs. Marshall is helping establish the standards and qualifications "from art to part" for the use of these advanced techniques and the parts produced using them in aerospace or elsewhere in the U.S. industrial base.

At-A-Glance

Propulsion system development requires new, more affordable manufacturing techniques and technologies in a constrained budget environment, while future in-space applications will require in-space manufacturing and assembly of parts and systems. Marshall is advancing cutting-edge commercial capabilities in additive and digital manufacturing and applying them to aerospace challenges. The center is developing the standards by which new manufacturing processes and parts will be tested and qualified.



Selective laser melting enables faster and cheaper component development.

Accelerating Design and Development of Propulsion Systems

As designers learn the capabilities of Advanced Manufacturing, the way they think is changing. The ability to rapidly create and test prototypes saves significant time between design cycles, as design concepts can quickly advance from drawings to test articles. A propulsion system subassembly that previously required multiple welds might now be 3-D printed all as one piece and test fired in less time and at much less cost than traditional manufacturing. A combination of experienced engineers and in-house resources enables Marshall to take a project from conception through manufacturing, finishing, and testing, resulting in flight-ready hardware and/or proven processes for use by partners during full-scale production.

Marshall houses a complete suite of digital manufacturing and support capabilities, including Structured Light Scanning, Non-Destructive Evaluation, Manufacturing Simulation, Manufacturing Planning and Execution, and inspection and machining technologies.

This one-piece injector took just 40 hours to make with a 3-D printing machine, instead of the months needed by traditional manufacturing.

Advancing Manufacturing Technology for Future Needs

Marshall became involved in Additive Manufacturing when it was still an emerging technology and purchased one of the first printers in 1990, primarily for rapid prototyping. Today, the center team is using state-of-the-art 3-D printers that work with a variety of plastics and metals, including titanium, aluminum, Inconel and other nickel alloys widely used in aerospace manufacturing. In addition to its focus on manufacturing future propulsion systems, the Center is leading efforts to demonstrate 3-D printing technology in orbit — the first step toward in-situ resource utilization on orbit or at exploration destinations, a critical need for future long-duration and deep-space missions.

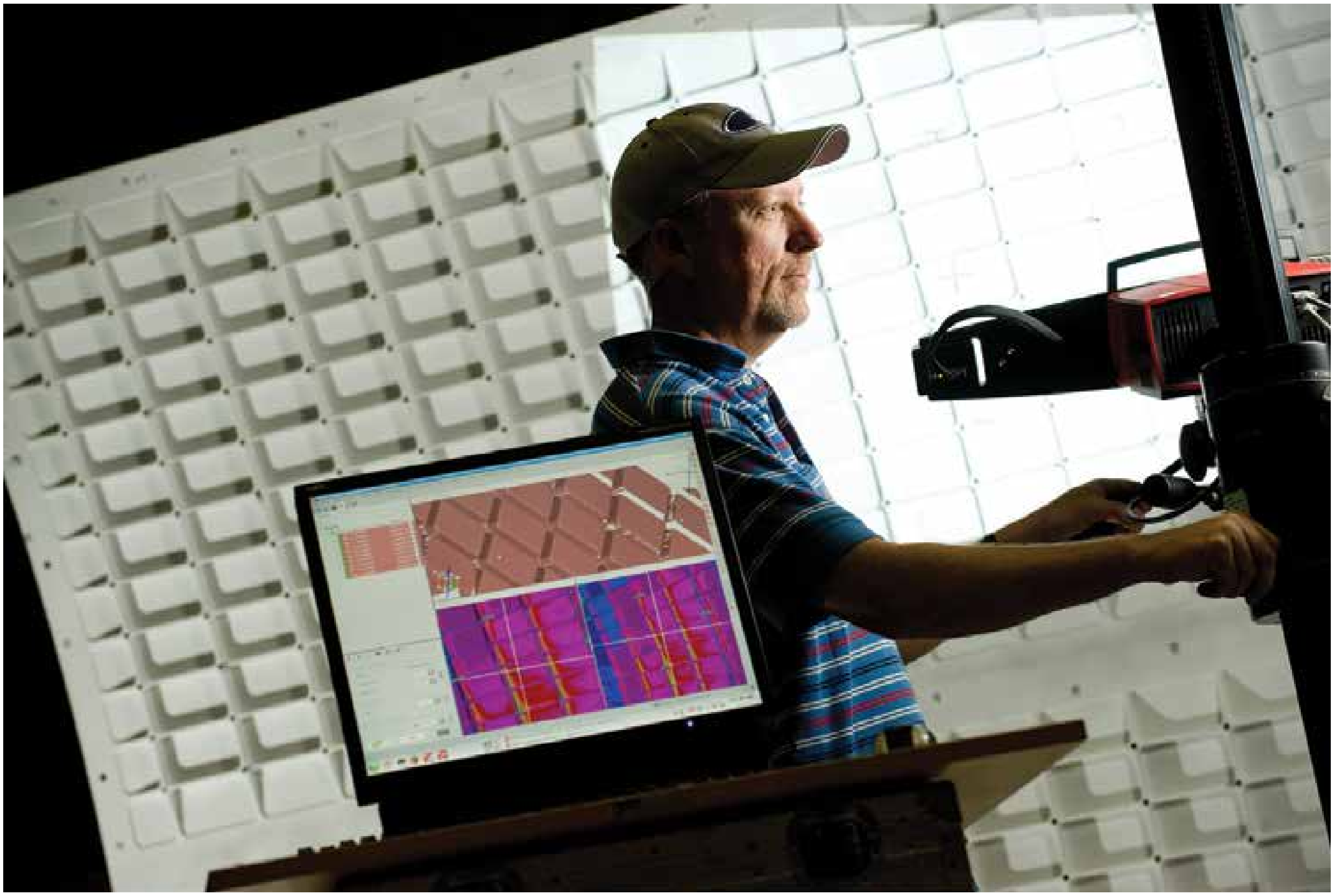
Additive Manufacturing technology for metals includes:

- Selective Laser Melting (Direct Metal Laser Sintering)
- Electron Beam Melting

Additive Manufacturing technology for plastics includes:

- Stereolithography (often used for flow cell models and cold flow testing, as the parts are water resistant and can be made see-through to channels inside)
- Fused Deposition Modeling (an extrusion-based technology that is gravity-independent and holds potential for development of in-space manufacturing)

Structured Light Scanning is also used to evaluate parts produced by 3-D printers or other methods by scanning and comparing the as-built version to the original computer design. Marshall teams working on two Orion Multipurpose Crew Vehicle Stage Adapters used it to show where large panels needed to be cut to precisely shape the 18-foot-diameter cone, saving millions of dollars on custom tooling. The technique was also used to scan heritage F-1 engines, and the scans were then used to fabricate needed tooling to disassemble the engine for testing.



Structured Light Scanning of Orion panels allows extremely precise fits, saving millions of dollars on custom tooling.

Structured Light Scanning technology includes:

- One Blue Light “Triple Scan” and other Blue Light 3-D Scanners
- White Light 3-D Scanners

The capability allows for scanning almost anything, from items smaller than a dime to the size of a Boeing 747. It has been used to scan 40-foot-diameter barrel sections of a space shuttle external tank and Space Launch System tank sections.

Other scanning and Non-Destructive Evaluation inspection technology includes:

- Computed Tomography (CT) scanning
- Radiography
- Photogrammetry
- Ultrasonic techniques
- Electromagnetic techniques
- Dye penetrants

Scanning works in concert with other digital manufacturing techniques such as manufacturing simulation to identify and address potential problems early in the design and production process, saving time and costly re-tooling or repair. The expertise and software available at Marshall can provide virtual fit checks, predict the buildup of material on a surface, reverse engineering, kinematic analysis, and much more.

Printing Propulsion Cuts Cost and Schedule

It looked like just another rocket test, one of thousands at Marshall Space Flight Center over the decades. But the firing on June 11, 2013, was a milestone — it was the first involving a rocket engine fuel injector that had been designed, 3-D printed in one piece, and hot-fire tested completely in-house at Marshall.

The Propulsion Systems Department designed the injector, which the Materials and Processes Laboratory 3-D printed in one piece by sintering Inconel steel powder in a process called Selective Laser Melting. It took only 40 hours to print each of two injectors. Then came minimal machining and inspection by scanning.

Using traditional methods, this would have taken six months to fabricate, with four parts, five welds, detailed machining, and a price tag of more than $10,000 per injector. Instead, it took just about a month for the 3-D-printed injectors to go from designs on a computer screen to parts in the line of fire during a series of Space Launch System acoustic tests, at a cost of less than $5,000 per injector.

Engineers compared the performance of the 3-D-printed injectors to those produced with multiple parts and traditional welds, and saw no difference in performance. In fact, post-test inspection of the printed injectors found them in such excellent condition that plans are for them to be re-used in upcoming tests.

Marshall's 3-D printed injectors were produced at half the cost and six times faster than traditional manufacturing.

Large-Scale Manufacturing

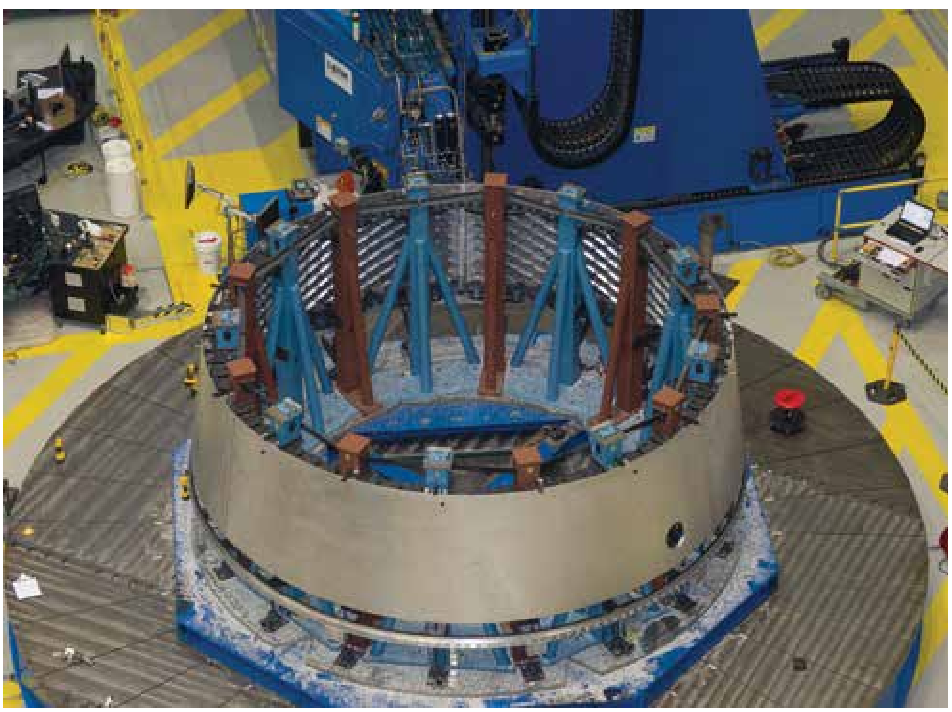
Advancing State-of-the-Art

Marshall is a leader in large-scale manufacturing for aerospace, involved in the production of everything from the Redstone rocket to the Saturn V, space shuttle propulsion elements, International Space Station (ISS), and now the Space Launch System (SLS). Marshall has helped "build big" for more than five decades and is uniquely equipped with the expertise and technology to continue leading the development of groundbreaking welding and composite techniques and processes for large-scale manufacturing. The Center also manages the resources and production of tanks, panels, and other structures at the Michoud Assembly Facility in Louisiana, supporting SLS and other missions as well as commercial efforts.

The Center conducts path-finding research and development on large-scale manufacturing tools and processes to be implemented by industry partners in production. This reduces risk, decreases costs, and increases mission success — particularly for human space exploration missions, which by their nature demand large-scale structures.

At-A-Glance

Large, complex space systems — whether launch vehicles, human habitats, or scientific observatories — continually "push the envelope" of large-scale manufacturing capabilities. Marshall Space Flight Center researches, designs, develops, tests and evaluates new processes to be implemented by our contractor partners during production, using both cutting-edge hardware and digital design optimization solutions. Together we are finding new ways to minimize cost and schedule and to enhance the performance of mission elements requiring large-scale manufacturing and production.



Marshall tests manufacturing process and tools for the Orion structural test article to troubleshoot before full-scale production begins.

Pioneering Techniques for Industry Application

Before embarking on new large-scale manufacturing efforts, Marshall uses digital design tools and models of planned manufacturing facilities to determine any potential logistical difficulties or hardware risks in planned manufacturing flows. By creating digital models of the facilities and tools, the Center can identify potential issues with clearances, handling procedures, or fabrication processes before the facilities are even completed. With the significant costs involved in developing and outfitting large-scale manufacturing facilities, this represents significant reductions in both cost and schedule.

Welding and metals are at the core of manufacturing for space launch vehicles and other large-scale structures. Marshall's team has long pioneered welding techniques and holds many patents, with a specialization in optimizing advanced joining processes, taking them from the laboratory to full-scale flight hardware and structures.

The friction stir process developed by The Welding Institute has been advanced at Marshall, which began using it in the 1990s with difficult aluminum lithium alloys while building the ISS. Marshall invented a retractable pin tool for friction stir welding, developed a self-reacting friction stir process, matured friction pull plug welding, developed techniques for other alloys, and established engineering requirements and design data used throughout the aerospace industry. Today, the Center is developing tools and techniques for ultrasonic stir welding and thermal stir welding, a derivative of the friction stir process used with nickel-based and titanium alloys or high-temperature steels. These processes may dramatically reduce the size and cost of weld technology and be suitable for in-space welding. The method was recently demonstrated in welding the Orion Stage Adapters and Multi-Purpose Crew Vehicle simulator.

Marshall also specializes in the use of composite materials for launch vehicles and space structures. The Center has developed a variety of composite articles for propulsion systems and launch vehicles, including cryogenic tanks, test panels, rocket motor cases and fairings. Recent activities include work with commercial partners to develop and test composite cryogenic hydrogen tanks. Switching from metallic to composite tanks could result in a dramatic reduction in mass, greatly increasing the performance of future space systems, including the SLS.

Marshall and Michoud Assembly Facility equipment has been used to manufacture components for the next-generation lightweight tank program and a number of launch vehicle programs, including the X-38. Marshall is also working with the NASA Engineering and Safety Center (NESC) to develop and test Composite Overwrap Pressure Vessels and was involved in the NESC study of a full-scale Composite Crew Module as a light-weight alternative to the Orion Multi-Purpose Crew Vehicle design.

Marshall evaluated a Composite Crew Module as a much lighter alternative to the baseline Orion design.

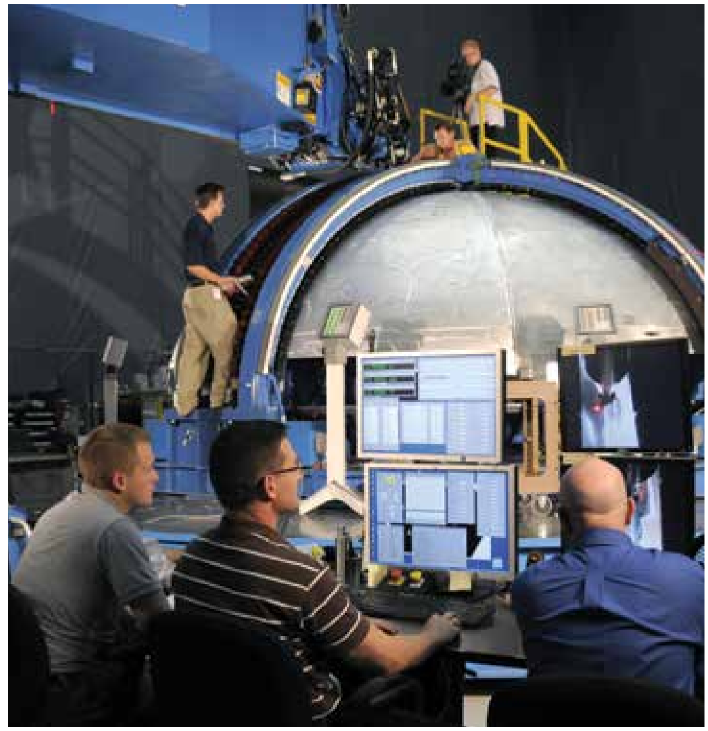
Sustaining Engineering Support for Large-Scale Production

Marshall's facilities are often used to provide sustaining engineering support to full production facilities by troubleshooting problems that arise during manufacturing at the Michoud Assembly Facility or in private industry. Commercial partners have also used the Center's facilities, which include the same advanced welding, composite, and other tools used at Michoud, while waiting for delivery or installation of their own equipment. Marshall's team has been called upon for failure analysis of Army Apache, Blackhawk, Chinook and other helicopter parts, as well as to help solve problems for other centers, government agencies and industry.

Comprehensive Large-Scale Manufacturing and Testing Facilities

The Center offers a full suite of support capabilities for large-scale manufacturing, including on-site inspection and non-destructive evaluation expertise and technology, including Structured Light Scanning, photogrammetry, microscopy, spectroscopy and chemical analysis.

Marshall's experienced team is complemented by the Center's unique collection of tools and technology. There is a broad range of advanced welding, composite and assembly equipment, including seven friction stir welding systems; plug welding and fusion welding systems; four-axis filament winding machines; tape laying machinery; and more. In addition, the Center offers some rare and unique capabilities including:



Marshall's Robotic Weld Tool can handle the complex curvatures needed for launch vehicle fuel tank domes.

Welding

- Large Robotic Weld tool, with a 30-foot-diameter turntable, capable of complex-curvature weldments to 36 feet in diameter and 22.5 feet tall
- A pair of Vertical Weld Tool 1, capable of welding up to 20 feet tall with a range of diameters from 8 feet to 40 feet
- Vertical Weld Tool 2, can weld up to 25 feet tall with a range of diameters from 10 feet to 40 feet
- Vertical Assembly Tool for welding 18-foot-diameter circumferential joints
- Three unique panel weld systems in support of weld development
- Two Friction Plug Weld systems
- Thermal Stir Weld system for welding high-strength alloys

Composites

- 18 x 20-foot autoclave with 2-ton hoist
- 9 x 12-foot autoclave
- 4 x 6-foot autoclave
- Curing ovens ranging from 2 x 2-foot to 20 x 60-foot
- 5,000-square-foot clean room and other clean rooms and work areas
- 400-square-foot airlock with 2-ton hoist

Advanced welding tools are used at Marshall to reduce project risk before flight hardware begins production.

Friction Stir Welding the Shuttle External Tank

Along with Skylab and other projects in the decades after Apollo, Marshall managed the design, testing and manufacture of the largest single element of the space shuttles: the 27.6-foot-diameter, 15-story-tall external tank. The drawings, materials analysis, specific fusion welding techniques, and processes developed at the Center were put into production for the tanks at the Marshall-managed Michoud Assembly Facility.

When it was later decided to convert the tanks to stronger and lighter (but more difficult to weld) aluminum lithium, Marshall's welding team pioneered new techniques for their manufacture. The then-new friction stir weld process was the perfect solution. Michoud was able to continue production with its facilities while Marshall configured its tools and technology for prototypes, testing, and demonstrations of techniques to weld and manufacture the large barrels for the tanks. The experience and test data enabled the Marshall team to write equipment specifications, acceptance criteria, and other lessons and information that were adopted by industry.

When problems arose after the new tanks went into production, Marshall's data and facilities were key to finding solutions. The kind of off-line research and troubleshooting of large-scale manufacturing techniques available at the Center is rarely found in industry, which is necessarily focused on production. This capability was leveraged again during the development of the Ares launch vehicles, and is currently being used to develop test articles and production processes for the SLS.

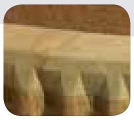
Marshall engineers tested new friction stir welding techniques before shuttle external tank production began on flight hardware.

Marshall Space Flight Center

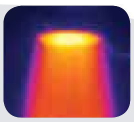
Space Transportation and Systems

Space Transportation and Systems

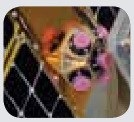
- Advanced Concepts and Systems Analysis



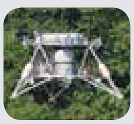
- Structural System Design and Analysis



- Thermal and Fluid Systems



- Avionics and Electrical Systems

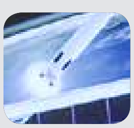


- Guidance, Navigation, and Control

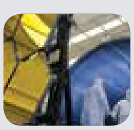
- Flight Software

- Payload Systems

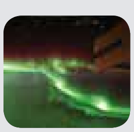
- Mission Operations



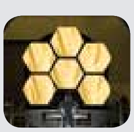
- Life Support Systems Design and Development



- Environmental Test



- Space Weather and Natural Environments



- Optical Systems

Advanced Concepts and Systems Analysis

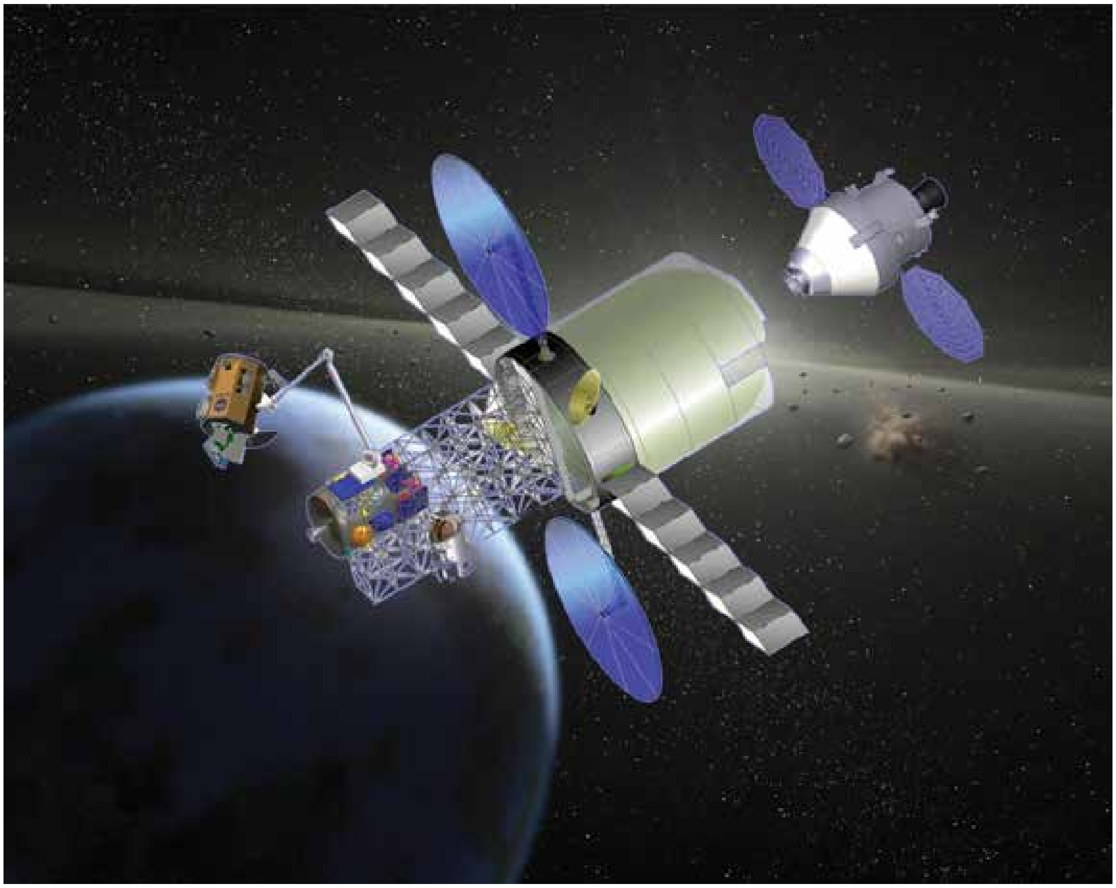
Rapid Architecture Solutions

Advanced space systems are growing more complex in size and scope, making systems analysis and engineering ever more critical to a successful mission, whether for free-flying satellites or human-rated vehicles. Decisions made early in design reverberate through design, development, operations, safety, and cost. Both programs and principal investigators need expert architecture studies done quickly.

With a collaborative and customer-focused approach, Marshall's Advanced Concepts Office offers expertise in advanced concepts and systems analysis to create a launching point for next-generation space systems. Using a multi-discipline approach, engineers provide rapid development and analysis of innovative solutions to difficult problems. The core team has decades of experience in both launch vehicle and space system concept design and offers physics-based analysis rather than simple database or analog lookup, yielding an end-to-end design capability for preliminary concepts.

At-A-Glance

Providing advanced concepts and powerful multidiscipline systems analysis, Marshall Space Flight Center's Advanced Concepts Office (ACO) specializes in high-fidelity pre-Phase A and Phase A concept definition studies for space exploration systems. For today's competitive environment, the ACO provides a rigorous, expedient, and cost-effective way to achieve every mission's design goals.



Marshall conceived and assessed a Skylab-inspired habitat for deep space exploration using the SLS.

Broad Experience, Deep Expertise

The ACO is unique throughout NASA for its breadth of experience in both space system conceptual analyses and integrated architecture. The office has studied Earth-to-orbit and in-space transportation systems and elements of exploration and discovery missions, including landers, habitats, planetary surface systems, and science systems. Well-known for its work on Earth-to-orbit missions, the ACO performs trajectory analyses, weights and sizing, vehicle structural analyses, and system level trades. The team also has expertise with in-space, exploration, and discovery studies. Work on in-space missions encompasses architecture, operations and mission analysis, technology assessments, in-space element definition, and habitation and crew systems. On exploration and discovery studies, the ACO has provided customers with mission concept definition and spacecraft concept designs for scientific and robotic exploration, human exploration, and technology demonstrations.

By conducting tailored, highly focused one- to four-week studies, Marshall's ACO provides services to customers within NASA, the Department of Defense, universities, and throughout the commercial space flight industry. The office works alongside its customers to quickly meet project goals within the customer's unique requirements and establish a solid foundation for project and mission success.

Recent or Current Study Highlights

Marshall and the ACO are best known for their work with Earth-to-orbit vehicles, from small satellite delivery to super heavy lift. Marshall is a pioneer in propulsion, including chemical and cryogenic, nuclear electric interplanetary, solar electric, and solar sails. While propulsion and launch are Marshall's recognized specialties, the ACO has also been critical in the development of other mission areas, including:

- Human health, life support, and habitation systems
- Orbital vehicles from nano-satellites to large vehicles, including the Hubble Space Telescope and Chandra X-ray Observatory
- Planetary surface systems

Marshall is partnering with Johns Hopkins University and other leaders in the science community on a ground-breaking astrophysics mission concept to design the Wide Field X-ray Telescope (WFXT), a proposed successor to Chandra. This telescope's innovative wide-field X-ray optics design will cover about 1,000 times the area of the Chandra telescope deep field survey with greater sensitivity than any previous X-ray telescope. In 2012, the ACO completed a conceptual spacecraft design of the WFXT to demonstrate the feasibility of the mission. The collaborative multidiscipline design approach called on experts from across spacecraft disciplines, including configuration, avionics, thermal, power, propulsion, guidance and navigation, and structures. Positive results of the study supported Marshall's decision to purchase equipment to reduce the risk of replicated optics for WFXT.

ACO's thirty-day feasibility study of the Wide-Field X-ray Telescope informed key decisions.

Resources for Rapid Delivery of Robust Ideas

The ACO combines the necessary expertise with the latest design and analysis tools to translate ideas into robust engineering designs. Much of the office's modeling and high-fidelity animation for engineering analysis uses industry-standard computer tools, enabling efficient sharing of information with customers and other project teams. To support the specialized nature of many conceptual design studies, the ACO has created a suite of custom tools that enable tasks such as spacecraft performance and subsystem design analysis.

Built on a comprehensive systems-based approach, the ACO's innovative design process consists of three collaborative phases, often executed in parallel to speed design iterations and lead to faster solutions:

- **Architecture Definition** is an iterative process involving analysis tasks to define the mission profile and identify mission options that compose the mission and vehicle trade space.
- **Vehicle Definition**, closely linked to the architecture definition process and based on requirements derived from the mission analysis, forms the basis for vehicle performance and subsystem design assumptions.
- **Systems Engineering** processes are conducted in parallel with the mission and vehicle definition processes and, to the extent possible, for pre-phase A and conceptual design studies.

The ACO offers customers a state-of-the-art collaboration space, the Advanced Concepts Design Center (ACDC), to support the development and analysis of new mission and space vehicle concepts. ACDC gives mission teams significant opportunities to gain efficiency and improve processes during the concept design phase and supports project teams of up to 25 people. The room facilitates creative thinking and streamlined access to strategic models and operational information. A flexible layout allows the ACDC to be quickly reconfigured to accommodate changing needs of the study team.

In the ACDC collaborative environment, teams quickly develop and assess design concepts.

Beyond Earth Orbit: SLS Utilization Mission Opportunities

NASA is developing technology now to prepare for large space missions far beyond Earth orbit. With the Space Launch System (SLS), NASA and its partners will explore asteroids, the moon, Mars — and beyond. The SLS is designed to be flexible and evolvable and to meet diverse mission needs such as retrieving samples from the outer planets, launching deep space habitats, and enabling human exploration of Mars.

Leveraging the extensive experience of Marshall engineers in both launch vehicle and space system concept development, the ACO identified more than 40 missions that SLS would enhance — including Earth orbit, lunar, planetary, near Earth asteroid, and comet — many rooted in decadal surveys conducted by the National Research Council. From these studies, the ACO identified four major benefits overall to the utilization of the SLS: reduced trip time, reduced complexity, increased payload, and increased reliability.

Skylab II (SLS-derived Deep Space Habitat)

Skylab II is a concept that uses an empty SLS propellant tank for a deep space habitat. Similar to the original Skylab (operated 1973-74), it is a low-cost, low-risk solution benefiting from the SLS large diameter and heavy-lift capability for a single launch delivery. It provides ample volume for the crew and operations. Commonality with the SLS ensures launch vehicle compatibility with minimized development time.

Jupiter Europa Orbiter Mission

The ACO's studies reveal that with an SLS launch capability, exploration of Jupiter's moon Europa can be completed faster and return more data than with existing launch vehicles. The SLS could send this spacecraft directly to Jupiter, reducing the need for gravity-assist trajectories that increase transit time and mission risk.

Mars Sample Return Mission

A Mars Sample Return mission under consideration consists of three spacecraft. The ACO determined that the SLS can provide a single-launch Mars Sample Return solution, in contrast to the baseline three-launch architecture, greatly reducing mission risk and increasing sample return mass by a factor of 10.

ACO continues to evaluate the many scientific and exploration missions enabled by the heavy-lift capability of the SLS.

Structural System Design and Analysis

Minimizing Mass, Ensuring Integrity

From concept development through mission execution, Marshall Space Flight Center delivers customized, affordable, and optimized structural systems design and analysis solutions, ensuring the physical integrity of spacecraft and launch vehicles in all applicable environments.

The structure of any hardware-based system is its backbone, supporting components in all expected natural and induced operating environments. Marshall's Structural Systems Design and Analysis (SSDA) capability uses a broad suite of methods and tools to ensure the physical integrity of prototype, development, ground, and flight hardware systems. From the simplest payloads to the most complex spacecraft and launch vehicle systems, from concept initiation through mission operations, Marshall provides comprehensive SSDA capabilities.

At-A-Glance

Marshall is a leader in the structural design of launch vehicles and in-space staging crucial for future scientific and exploration missions. Collaboratively in the design process, Marshall offers a full spectrum of design and analysis capabilities to provide independent assessment, insight/oversight, or in-house development as needed for missions. State-of-the-art tools and unique facilities serve a diverse customer base across the Agency, as well as partnerships with other government agencies and the aerospace industry.

Advanced modeling tools ensure that structural designs meet requirements for both ground processing and in-space operations.

STS-133 External Tank Insulation

Throughout the life cycle of the Space Shuttle Program, Marshall engineers collaboratively provided design and analysis capabilities and assessments for the individual missions.

On November 5, 2010, launch of Space Shuttle Discovery on STS-133 was scrubbed due to a small hydrogen leak at a ground umbilical connection. Routine visual inspections of the external tank revealed an unusual crack in the sprayed-on foam insulation at the forward end of the intertank. Repairs showed a more serious problem — an underlying aluminum stringer, or structural stiffener, had fractured. An adjacent stringer was similarly fractured, although the foam over it appeared undamaged. Understanding the cause of the fractures and developing a repair concept were required before launch. Marshall, as managing center for the external tank project, coordinated the work with the prime contractor, Lockheed Martin, and other NASA organizations. Marshall brought to bear a wide array of capabilities in material science, structural analysis, and structural testing.

Non-destructive X-ray inspection revealed three more cracked stringers. Forensic analysis of sections removed from the first two cracked stringers revealed no pre-existing cracks or defects and that the stringers fractured in overload with no evidence of fatigue. Testing concluded that the aluminum material satisfied all specifications, including minimum strength and elongation.

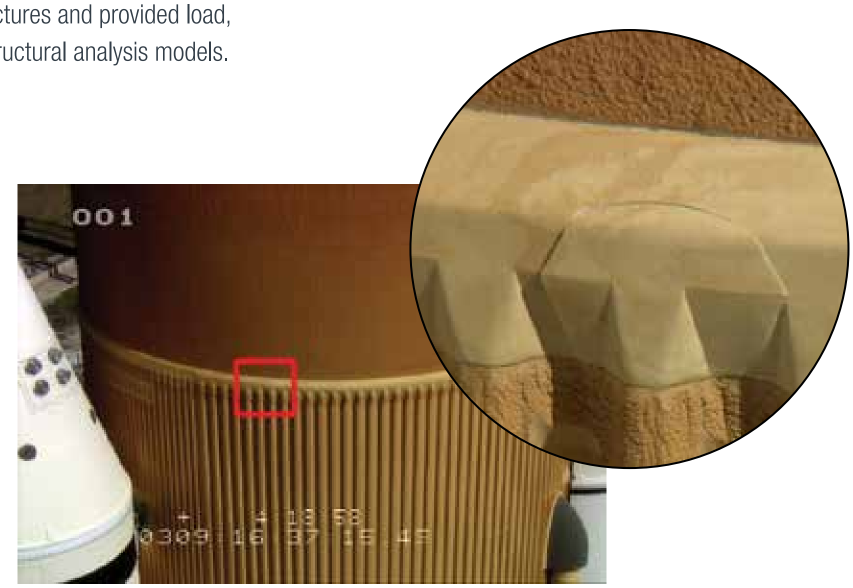
Marshall engineers augmented Lockheed Martin in studying the stringers under various temperature and loads and developed a structural test program for static load testing of individual stringers. A test apparatus simulated stringer deflections experienced during cryogenic loading. This re-created the stringer fractures and provided load, deflection, and strain data to validate structural analysis models. More than 25 stringers were tested.

The cause of the stringer failures was a combination of material being less capable than expected and stresses being greater than expected. The reduction in material capability was attributed to an untypical fracture toughness behavior observed in two lots of aluminum material from which all failed stringers were fabricated. Checking fracture toughness had not been required. The exact metallurgical failure phenomenon was never identified. It was determined that more than half of the approximately 100 stringers on the STS-133 external tank were likely from either of the two suspect material lots. The greater-than-expected stresses were attributed to unexpected assembly stresses that combined with cryogenically induced deflections. Analysis, testing, and inspection provided evidence of several possible sources of assembly stress, including geometric irregularities from the stringer-forming process and stresses from the fastener installation. Analyses also showed that the cryogenically induced stresses were more severe at some stringer locations than others.

All fractured stringers were repaired with sections taken from new stringers. Analyses by the Marshall structural analysts ensured that the repair did not create unintended and detrimental stress concentrations. The Marshall test apparatus demonstrated the effectiveness of the stringer repair.

Working independently but cooperatively with the prime contractor, Marshall engineers enabled the Project Office to present a comprehensive explanation of the failures with unified findings and recommendations to the Space Shuttle Program. STS-133 successfully launched on February 24, 2011, beginning the final mission of Discovery.

Marshall determined the cause of cracked stringers on STS-133 and evaluated structural integrity of the replacements.

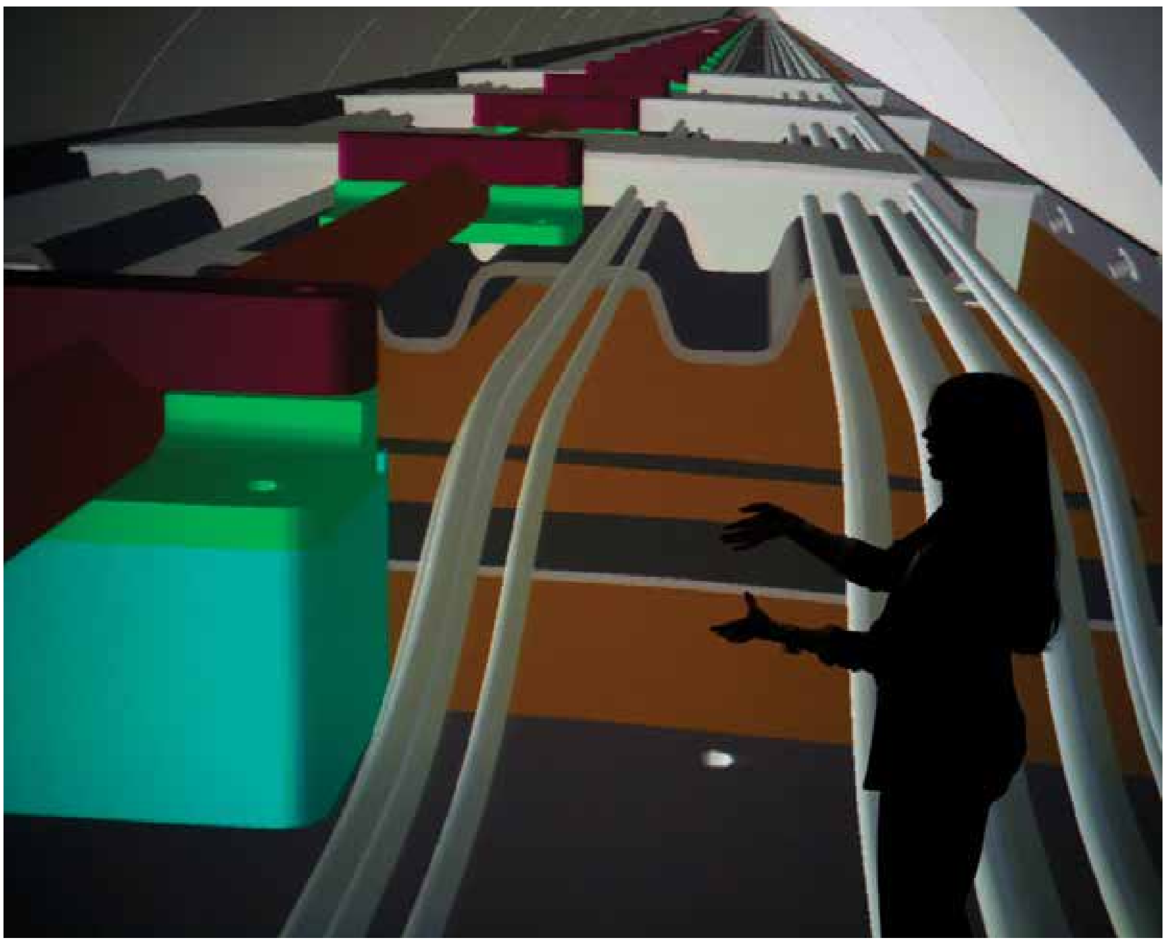


Cross-cutting Discipline Support for Space Systems
Marshall's structural designers and analysts continually balance the physical integrity of the system with the lowest practical weight and most affordable manufacture.

Scaling to meet a wide range of customer requirements, Marshall delivers integrated teams of structural design and analysis engineers for large, complex programs and projects. These range from the Space Launch System (SLS) to single, multi-discipline engineer support for small flight projects or science payload development.

Marshall engineers are experts in state-of-the-art design and analysis software tools to develop and analyze complex 3-D models and 2-D wireframe drawings or schematics. These tools include:

- **Pro/Engineer** — Parametric, integrated 3-D CAD/CAM/CAE
- **Windchill** — Project collaboration and design data management
- **Pro/Mechanica** — Structural and thermal static and dynamic analysis software
- **Hypersizer** — Design, analysis, and optimization software for composite and metallic structures
- **Spaceclaim** — 3-D direct solid modeling software tool for digital prototyping, analysis, and manufacturing
- **Microstation** — 3-D/2-D modeling software and application integration platform
- **NASTRAN** — NASA Structural Analysis software



The Collaborative Engineering and Design Analysis Room (CEDAR) integrates multidiscipline computer-aided design for components of launch vehicles and spacecraft.

Responsive Facilities To Test and Validate Designs

Marshall's comprehensive spectrum of structural test capabilities complements and supports SSDA. These capabilities provide local, easy access for structural design and analysis testing and verification in laboratory and simulated space environments. Other tools include vibration test stands and tables, thermal and thermal-vacuum chambers, axial loading stands, and acoustic chambers. These tools test models and simulations of thermal, strength, dynamics, acoustics and vibration environments of structural hardware.

- **Mechanical Development Facility** (MDF) provides a safe, controlled environment to assemble and evaluate development, engineering, and prototype hardware. It is used for breadboard buildups, mechanical system checkouts/evaluations, and development of hardware mockups. The MDF can produce rapid prototypes for checking structural fit and assembly clearances when modifying existing hardware.
- **The Mechanical Fabrication Lab** enables structure and assembly research and development, test, and flight hardware. It validates structural design and analysis, and includes quality assurance processes such as in-process inspection, as-built configuration control, hardware traceability and process certification.
- **Small Space Vehicle Landing Stability Facility**, unique to Marshall, tests the stability of lander designs and supports structural design and verification efforts. A scale model of a lander — a Stability Test Lander (STL) — impacts a deck to correlate vehicle dynamics with models and tests whether the design will land safely.

Marshall structure designers and analysts have immediate access to onsite hardware fabrication and test facilities and engineering expertise. This access is a powerful enabler to completing tasks in a timely, thorough manner.

End-to-End SSDA Experience

Marshall is highly capable and experienced in SSDA development of diverse space systems and missions including:

Launch vehicles and in-space stages

- Space Launch System
- Constellation — Ares I upper stage and first stage
- Nanolauncher concepts
- Commercial Crew Integrated Capability (CCiCap) support
- Space shuttle external tank and solid rocket booster systems

Spacecraft and spacecraft systems

- Major spacecraft science observatories such as Hubble and Chandra
- Small satellites and Cubesats
- Lander concepts and demonstrations

International Space Station elements, facilities, and payloads

- Nodes and Multi-Purpose Logistics Module (MPLM)
- Environmental Control & Life Support System (ECLSS)
- Microgravity Science Research Rack (MSRR)
- Sample Ampoule Cartridge Assembly (SACA)

Technology development

- Advanced exploration systems and space technology projects

External customer projects

- DOD, commercial launch providers, automotive industry

Thermal and Fluid Systems

From State of the Art to Standard Practice

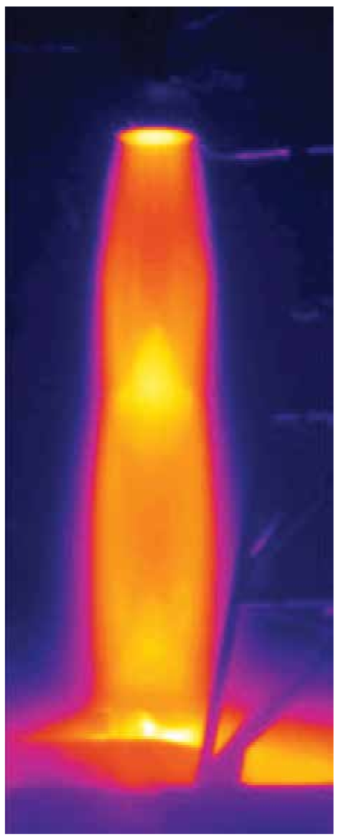
The development of launch vehicles, spacecraft, and associated payloads requires the capability to accomplish fluid dynamics and thermal design, analysis, and test activities to ensure the timely development of reliable systems and components that deliver the required performance. Marshall advances the state of the art in these disciplines, developing tools and analysis techniques that are adopted as educational and industrial standards.

Marshall's thermal and fluid dynamics systems capabilities are an extensive collection of expertise, methods, tools, and facilities used to ensure that launch vehicles and space systems are designed and built to reliably withstand the demanding environments in which they must operate. Marshall provides a targeted, sophisticated approach to every project and has created a national reputation and demand for its expertise and unique custom-developed tools.

Although a separate discipline, fluid dynamics is often an important aspect of thermal analysis, and the two disciplines often intersect.

Thermal Analysis: Every launch vehicle and spacecraft hardware system operates in extreme, complex, and interrelated thermal environments that must be understood and accounted for in the system's design to control and maintain all elements of the launch vehicle space system within its temperature limits in all phases of its mission.

Fluid Dynamics: Fluid flowing through or around a hardware system and/or component creates system-level and local-level structural loads and thermal environments that must be analyzed and designed for. The fluid behavior, loads and environments the system must account for are especially extreme and complex when high fluid velocities are involved.



Infrared analysis of engine tests verifies that designs will meet performance requirements.

At-A-Glance

From decades of experience on launch vehicles, space systems, and complex scientific observatories, Marshall Space Flight Center's thermal and fluid analysis engineers have developed an extensive suite of customized design tools and the expertise to quickly apply the right tools to find solutions that meet performance needs. Coupled with deep interdisciplinary reachback and unique test capabilities, Marshall's thermal and fluid capabilities are critical to enabling smart design.

Discipline Expertise and Broad Mission Experience

From the simplest payloads to the most complex spacecraft and launch vehicle systems, Marshall provides a full spectrum of capabilities for thermal and fluid dynamics engineering disciplines. Center capabilities support propulsion systems, launch vehicles, and upper stages; spacecraft and spacecraft systems; the International Space Station; advanced exploration systems; the Space Technology Program; and various external collaborations. Our legacy team offers 30 years of experience with heritage hardware and human spaceflight and has been sought out by commercial space partners for consultation and solutions.

A recent success of Marshall's unique analysis methods came about on the Orion Launch Abort System Attitude Control Motor (ACM) where a carbon fiber rope assembly gap closeout thermal barrier system was recommended and used. The analysis approach for this system, derived by Marshall, enabled quick functional assessment and implementation into the ACM hardware, ensuring that program milestones were achieved on schedule. Marshall's team offers not only analysis but also deep experience with the development, selection, and application of analysis tools needed during development.

Turning Unique Tools into Industry Standards

Marshall has a diverse array of software design and analysis tools and test facilities to support thermal and fluid dynamics capabilities. Several of the unique thermal and fluid dynamics tools that have originated from Marshall have been embraced by the private sector and incorporated into educational materials as industry standards.

Engineers at Langley used Marshall's GFSSP software to predict pressure and flow rates on the IRVE-3 experiment before flight.

Generalized Fluid System Simulation Program (GFSSP)

The GFSSP code is a finite volume-based thermo-fluid system analysis tool, with emphasis on thermodynamics. It was developed at Marshall in 1996 to analyze propulsion system and internal flow of turbo pumps for the Fastrac engine. Its design is user-friendly, with an intuitive graphical user interface, robust solver, and extensive training materials and support.

GFSSP's capability has been regularly enhanced to improve its modeling capability and user interface, having gone through six incarnations with multiple upgrades. The code can be used in any kind of flow circuit to perform steady state or transient analysis of pressure, flow rate, and temperature distribution.

It received the NASA Software of the Year award in 2001 and currently has several hundred users across the Agency, Air Force, Navy, Army and private industry. An educational version of the code is being used in several U.S. universities for teaching thermal design to the next generation of engineers.

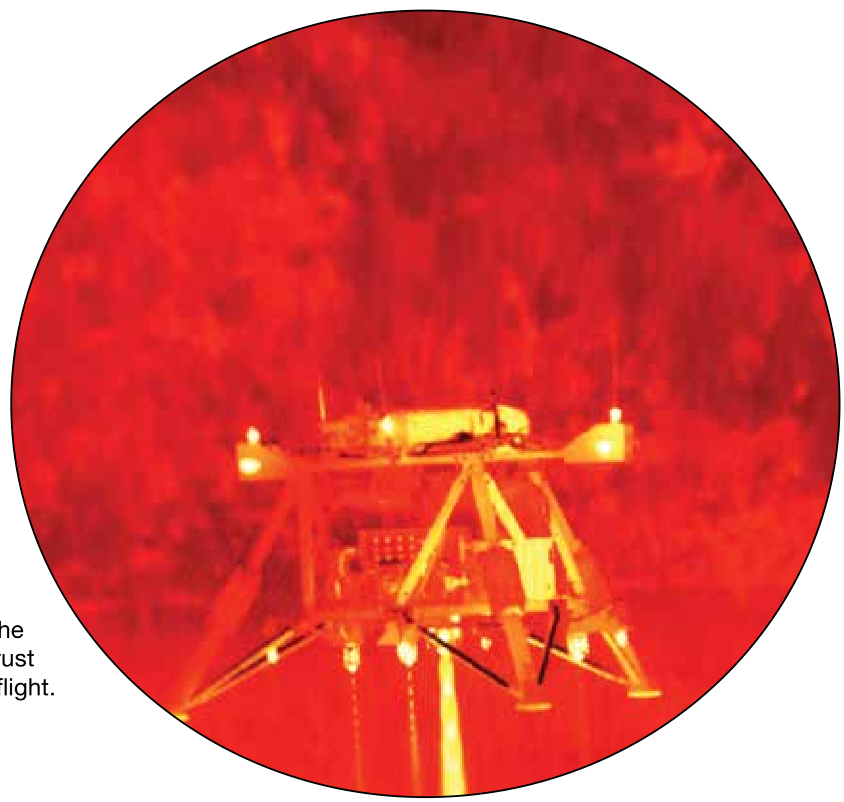
GFSSP was used by Langley Research Center to design the inflation system of Inflatable Reentry Vehicle Experiment (IRVE3). The purpose of this technology is to protect a spacecraft when entering a planet's atmosphere or returning here to Earth. IRVE3 successfully flew in July 2012. GFSSP prediction of pressure and flow rate in the inflation system during flight matched very well with the flight data.

Infrared Thermography

The Marshall thermal analysis team specializes in infrared thermography, the acquisition and analysis of thermal information from no-contact thermal imaging devices. Of particular note, the team specializes in calibrated high-temperature infrared thermography through the use of sophisticated cameras.

The specialty consists of a sophisticated network of cameras, data computers, data networks, remote triggering, and IRIG timing and serves a variety of customers. In environments and tests where direct contact is not possible — or is even dangerous — or results are not measurable by other methods, infrared imaging can safely "see" results that other instruments cannot. The cameras can capture plume structure, debris fallout, or temperature differentiations that provide valuable test data that could prevent potential problems.

Collaborations and customers include the Space Shuttle Program, International Space Station, Constellation's Altair lunar lander and Ares launch vehicle, J-2X engine development, and SLS materials analysis. These improved thermal and fluid analysis tools are also incorporated into existing test facilities at Marshall, such as the X-ray and Cryogenic Facility and the Hot Gas Facility.



Infrared thermography of the Mighty Eagle lander shows thrust plume structure during a test flight.

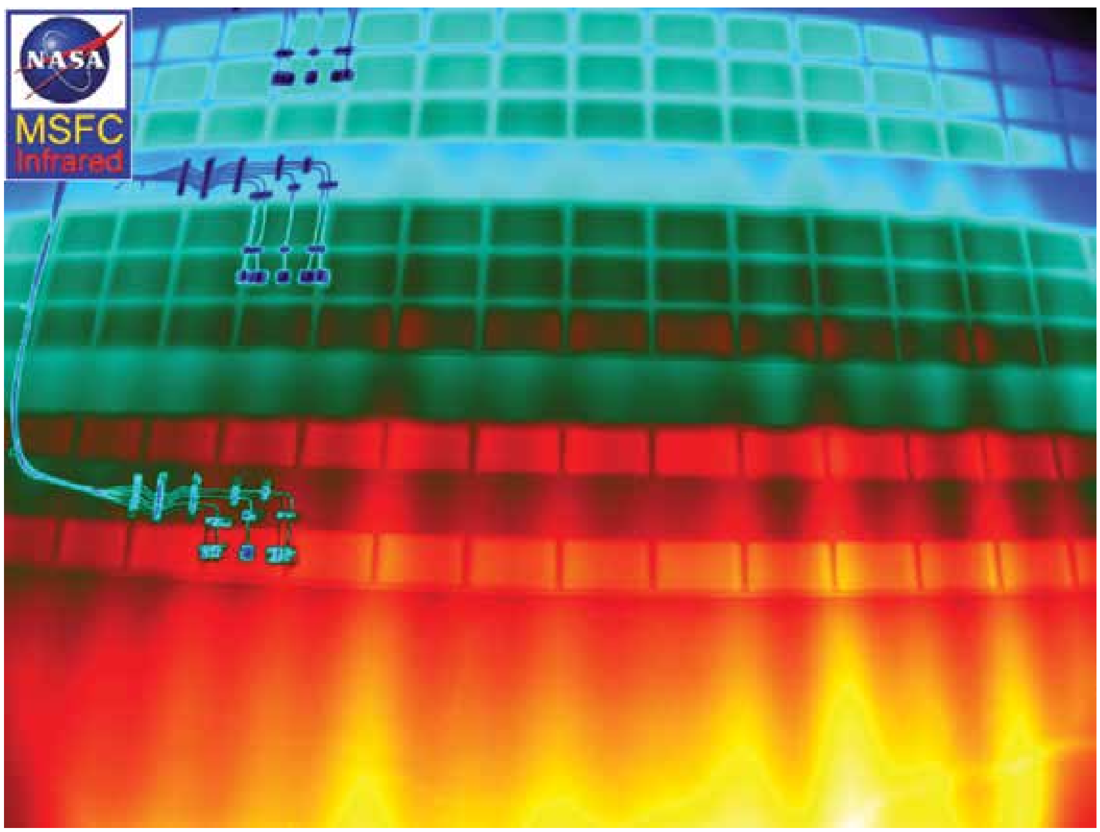
Improving Data Capture for Engine Testing Capabilities

The SLS upper stage J-2X engine was tested at Stennis Space Center's A2 test stand from February 2013 to April 2013, using a regenerative-cooled nozzle extension that further expands the plume for higher specific impulse.

The analysis team requested infrared thermography to validate the predicted temperatures. Thermocouples installed on the nozzle extension provided point temperature measurements, but it was impossible to cover the entire assembly due to the high cost.

A team of Marshall and Stennis engineers and technicians designed, constructed and installed two new clamshell infrared camera windows and housing to measure nozzle temperatures. The cameras were able to determine that the test stand diffuser coolant water and purge gas were preventing the extension from reaching the designed temperature profile. The camera provided data to reduce the coolant water and purge to obtain a more "flight-like" vacuum environment for the nozzle extension. The cameras also detected a hot streak that was not detected with the thermocouple instrumentation.

This methodology is being incorporated in other similar testing environments, providing a data capture ability that has always been desired but has not been available until now.



Avionics and Electrical Systems

Managing Costs Through Comprehensive Architecture Design

In complex space system development, such as launch vehicles, contractors are responsible for optimizing their portion of the development. This often leads to extensive reworking to resolve disconnects between systems. By managing and/or designing avionics architecture, Marshall contributes to lower cost, reduced schedule complexity, and potentially higher overall system performance.

Marshall has developed avionics systems for key Agency missions such as the Environmental Control and Life Support System aboard the International Space Station (ISS) and continues to do so for the Space Launch System (SLS). The avionics are an integral part of any spacecraft or science instrument, enabling command and control during flight operations.

At-A-Glance

Avionics and electrical systems provide the "nervous system" of launch vehicles and spacecraft, linking diverse systems into a functioning whole. In systems this complex, affordability and stability in the design process are challenges. Government-managed architectures help minimize the number of change orders as systems evolve during design and preserve the incentive to implement a cost-optimized, objectively designed architecture. Marshall can provide both in-house design and independent validation and verification after fabrication of subsystems by industry partners and maintains unique end-to-end system test capabilities.

Integration testing with flight hardware is key to reducing cost and maintaining schedule.

FASTSAT Avionics Architecture

Enables Rapid Development and Lowers Mission Costs

For two years, NASA's FASTSAT operated in orbit, conducting six science and technology experiments. FASTSAT used a distributed avionics architecture designed and developed at Marshall with multiple avionics test beds working in parallel to accelerate hardware and software testing. This allowed the team to go from the spacecraft's preliminary design review to final flight hardware in just 12 months. Marshall developed, tested, launched, and operated the ~400-pound microsatellite, using commercial-off-the-shelf hardware, in partnership with the Department of Defense (DOD) Space Test Program (STP), Dynetics, and VCSI.

The Marshall-defined avionics architecture reduced costs and the risk of time-consuming redesigns during subsystem integration. Working with industry partner Dynetics, Marshall's top-level architecture governed each component of the avionics system, ensuring compatibility and adequate power and signal resources for the operation of all six of FASTSAT's experiments. On-board storage for flight data was also critical, as the average contacts with ground stations were only a few minutes long. Even within these limitations, the mission delivered 17 GB of data from orbit, while receiving thousands of lines of code to update the flight computer and instrumentation during the mission, optimizing the scientific and technology development value of the flight.

FASTSAT's distributed architecture led to a very rapid development schedule.

Marshall's avionics capability enabled the launch vehicles of the past, including Apollo and shuttle, and progressed to the design and development of many scientific payloads that flew on shuttle scientific missions. More recently, Marshall has expanded its knowledge base into the design, development, and test of many of the electrical components that make up the Environmental Control and Life Support System (ECLSS) and the Material Science Research Rack (MSRR) in service on the ISS. Marshall has also supported missions from the large Hubble Space Telescope and Chandra X-ray Observatory to the more recent and much smaller Fast, Affordable, Science and Technology Satellite (FASTSAT) as well as instruments on the Tropical Rainfall Measuring Mission (TRMM) and the Geostationary Operational Environments Satellites (GOES). In support of SLS, Marshall has not only overall avionics architecture definition and oversight responsibilities but also in-house design work such as the cameras and video controllers to be attached to the Core Stage and Interim Cryogenic Propulsion System (ICPS).

Some of these projects require direct hands-on development and/or testing of the hardware, while others involve insight into and analytical integration of work performed by one or more prime contractors. In order to meet the Agency's needs in this area, Marshall has developed a rich set of avionics resources including state-of-the-art facilities and tools and broad disciplinary expertise in all aspects of avionics and electrical systems design, development, testing, and integration.

Unique Test Capabilities Ensure System Performance

Integrated Avionics Test Facility (IATF)

The IATF is an integrated hardware-in-the-loop laboratory that combines digital computer models, software, and avionics hardware to demonstrate real-time flight control of the Space Launch System during its flight. Avionics hardware is mounted in an approximation of its flight configuration, using the same cables and connectors that will be used in the final launch vehicle. The electronics architecture in the facility can be rapidly reconfigured as the avionics design for SLS matures, using a modular system of avionics boxes and other hardware to provide a complete representation of the SLS avionics system with the capability to simulate error conditions for trouble-shooting and validation of the system.

The IATF tests avionics in flight configuration to ensure system performance.

MSFC EMI Test Facility

The MSFC EMI Test Facility provides a comprehensive range of electromagnetic environmental effects testing services to a wide variety of customers. It has distinct capabilities in electrostatic discharge (ESD) and electromagnetic interference (EMI). A unique capability of the facility is its ability to assess lightning indirect effects. Sensitive spacecraft avionics and electrical systems can be damaged or destroyed by nearby lightning strikes during pad operations or ascent of the launch vehicle.

EEE Parts Physical Analysis

A unique specialty the EEE Parts team provides is the expertise and equipment to perform EEE parts physical analysis to determine the cause of EEE parts and assembly failures. Nanofocus real-time radiography, X-ray Fluorescence, 3D-CT (Computed Tomography), and Environmental Scanning Electron Microscopy and Optical Microscopy are just a few of the cutting-edge non-destructive techniques available.

End-To-End Avionics Discipline Expertise

Marshall's avionics and electrical systems capability is represented by several teams, each focused around a particular set of disciplines.

The Sensors, Data Systems, and Control Electronics team performs research, design, and development of electronic circuits and systems. Testing and evaluation is conducted in a variety of laboratories ranging from basic electronics to audio and sensor characterization chambers. These facilities support a variety of customers in the development of experiments to control instrumentation for propulsion elements on space vehicles.

The Radio Frequency Systems team analyzes RF systems for both communication and range safety for launch vehicles and satellites. The RF team also has expertise with Global Positioning Satellite (GPS) systems, including a GPS simulator, which also supports the GN&C Hardware team.

The **Electrical Integration team** designs and integrates avionics systems and hardware for spacecraft, payloads, and their associated electrical ground support equipment.

The Electrical Power Branch runs the gamut from research through test and evaluation of flight and ground electrical power subsystems (EPS). The team provides power electronics design, development, test, and analysis, circuit simulation, power quality compliance, and solar arrays, as well as design of custom electromagnetic and isolation transformers and inducers.

The E3 team provides engineering and requirements development and tailoring in electromagnetic compatibility; electrostatic discharge (ESD); electrical bonding; and lightning protection and test services for electromagnetic interference, power quality, ESD, and lightning indirect effects.

The Parts, Packaging & Fabrication team provides electro-mechanical design, analysis and assembly of space flight and ground hardware. Engineering capabilities include mechanical design, printed wiring board design, thermal analysis, EEE parts selection assistance, parts screening, and design support. In addition, this branch provides EEE Parts Obsolescence Management — a unique capability within NASA to manage electronic parts for a program that has become obsolete.

Guidance, Navigation, and Control (GN&C)

Efficient, Responsive, and Effective

The GN&C capability is a critical enabler of every launch vehicle and spacecraft system. Marshall applies a robust, responsive, team-oriented approach to the GN&C design, development, and test capabilities. From initial concept through detailed mission analysis and design, hardware development and test, verification and validation, and mission operations, the Center can provide the complete end-to-end GN&C development and test — or provide any portion of it — for launch vehicles or spacecraft systems for any NASA mission. Recognized as the Agency's lead and a world-class developer of Earth-to-orbit and in-space stages for GN&C, Marshall is a key developer of in-space transportation, spacecraft control, automated rendezvous and capture techniques, and testing.

The GN&C capability provides:

- **Mission Planning** — orbit and orientation design and planning, launch opportunity, on-orbit lighting and viewing analyses, rendezvous analysis and planning, and mission modeling and simulation.
- **Ascent Trajectory Design and Dynamics Simulation** — Ground-to-space path design and optimization, vehicle and propellant sizing, crew emergency abort range (ground) safety analyses, lift-off and stage separation simulation, and complete 6 degrees-of-freedom full vehicle simulation and statistical analyses to ensure safe flight.
- **Guidance** — ascent, on-orbit, rendezvous, planetary approach, and landing — all mission phases.
- **Navigation** — system architecture trade studies, sensor selection and modeling, position/orientation determination software (filter) development, architecture trade studies, automatic rendezvous and docking (AR&D), and Batch estimation — all mission phases.
- **Control** — algorithms, vehicle and control system requirements and specifications, stability analyses, and controller design, modeling and simulation.
- **Sensor Hardware** — selection, closed loop testing and qualification; design, build, and calibrate specialized sensors.

At-A-Glance

Guidance, navigation, and control capabilities will be needed for today's launch and tomorrow's in-space applications. Marshall has developed a GN&C capability with experience directly supporting projects and serving as a supplier and partner to industry, DOD, and academia. To achieve end-to-end development, this capability leverages tools such as the Flight Robotics Lab, specialized software tools, and the portable SPRITE small satellite payload integration environment. The versatile team also provides an anchor and resource for government "smart buyer" oversight of future space system acquisition, helping to manage overall development costs.

Marshall qualifies flight guidance components such as thrust vector control actuators.

Broad Experience with Spacecraft of All Shapes and Sizes

From conceptual mission design to detailed GN&C systems and software development to ground testing and engineering support during the flight, Marshall makes sure the spacecraft gets where it's going. The Center has a long history of designing, developing and testing GN&C systems for launch vehicles, satellites, landers, rovers, and space telescopes, including Shuttle, X-33, Ares, Chandra, and Hubble.

GN&C Architecture for the Space Launch System

Marshall provides critical GN&C components for the SLS — functional requirements and hardware specifications for the SLS Navigation hardware, the Redundant Inertial Navigation Unit (RINU) and the Rate Gyro Assemblies; and thrust vector control electronics. GN&C engineers for SLS are also developing the overall system architecture and all the algorithms that define how the flight software will work, navigate, guide, and control the vehicle. Hand-in-hand with this design work, the entire vehicle is dynamically simulated in extreme detail to drive out any problem areas in the design of SLS as it matures.

Advancing Automated Rendezvous and Docking/Capture (AR&D/C)

Automated Rendezvous and Docking/Capture is the process of bringing two spacecraft together in space. This particular aspect of space travel is particularly challenging, and GN&C has its own specialized GN&C has its own specialized algorithms, software, and sensors to accomplish the delicate choreography involved. Marshall successfully flew a video guidance sensor on the space shuttle to test advanced AR&D/C technologies, and provided advanced video guidance system, software, and sensor suite testing for DARPA's Orbital Express. AR&D/C technologies and techniques are critical to existing programs such as the International Space Station (ISS) as well as for future missions such as orbital debris removal, spacecraft servicing, and asteroid exploration.

Very small spacecraft are taking increasingly prominent roles due to their relatively inexpensive cost. Marshall advances in AR&D/C and GN&C enable complex missions to be carried out with these small platforms. For example, the Fast, Affordable, Science and Technology Satellite (FASTSAT) successfully operated six science and technology experiments at low cost. Marshall designed and built the hardware and software, tested and integrated the parts, and supported its operations. Marshall also tested advanced GN&C systems on a small robotic lander, the Mighty Eagle.

The Flight Robotics Laboratory provides comprehensive testing on the world's largest air-bearing floor.

High-Fidelity Testing in Simulated Space Environments

A major component of GN&C system development is testing at all levels, from subsystem components to the fully integrated vehicle. Marshall boasts state-of-the-art testing facilities such as the Flight Robotics Laboratory (FRL) "flat floor" facility and the Contact Dynamics Simulation Lab (CDSL).

The FRL's epoxy floor is a 44-foot x 86-foot precision air-bearing floor, the largest of its kind in the world. A robotic arm is combined with a gantry to provide 8 degrees of freedom (DOF) for simulating relative motion with respect to a fixed target. This apparatus can handle test objects of up to 800 pounds. In addition, a dynamic lighting simulator can simulate the motion and brightness of the sun. These capabilities allow the FRL to test full systems, whole spacecraft, sensors, and cameras. In support of SpaceX, the FRL tested two Proximity Operations Sensors for the Dragon capsule.

Once GN&C system testing is finished, the CDSL tests how the spacecraft handles the contact of docking or capture. With up to a 20,000 lbs. capability, the CDSL can simulate the docking or berthing mechanism motion and interaction in 6-DOF as it would be in orbit. The CDSL has tested almost every U.S. docking and berthing mechanism developed, including extensive testing of the Common Berthing Mechanism and astronaut training for ISS assembly.

In addition to world-class facilities, Marshall also possesses cutting-edge simulation and software tools such as the Marshall Aerospace Vehicle Representation in C (MAVERIC) and the Tree Topology (TREETOPS) Multi-Body Dynamics and Control Analysis tool. MAVERIC is a high-fidelity 6-DOF tool to simulate a space vehicle's launch or flight, including all environmental, propulsion, and aerodynamic forces that it encounters throughout its mission. TREETOPS, and its launch-vehicle-specific relative, CLVTOPS, provide detailed, multi-body analysis of critical events such as lift-off from the launch pad, rocket booster separation, and spent rocket stage separation. These tools simulate the integrated design elements to prove that the vehicle's design can accomplish what the mission prescribes.

Marshall's Mighty Eagle Paves the Way for Future Landers

Marshall and the Johns Hopkins University Applied Physics Laboratory (JHU/APL) are advancing technology for a new generation of small, smart, versatile robotic landers to achieve scientific and exploration goals. NASA's Robotic Lander Test Bed, the Mighty Eagle, conducts test activities to prove the design of this new generation of robotic landers. Marshall and APL engineers conducted studies and tests to aid in the design of this new generation of multi-use landers for future robotic space exploration.

The vehicle is a three-legged prototype that resembles an actual flight lander design. It is 4 feet tall and 8 feet in diameter and, when fueled, weighs 700 pounds. It is guided by an onboard computer that activates the thrusters to power the craft's movements. Marshall is using the Mighty Eagle to mature the GN&C technologies needed to develop a new generation of small autonomous robotic landers capable of achieving the Agency's scientific and exploration goals.

The lander has been through several series of tests, verifying its ability to lift off, hover, transit horizontally across a target area, and descend safely. The GN&C team refined Mighty Eagle's ability to autonomously navigate, including a system recently fitted onto the vehicle for optical hazard avoidance. This will allow the spacecraft to detect potential hazards at a landing site and select a more suitable location before descending.

Mighty Eagle's GN&C system enabled it to autonomously lift-off, traverse, and land successfully.

Flight Software

Agile Development for the Toughest Missions

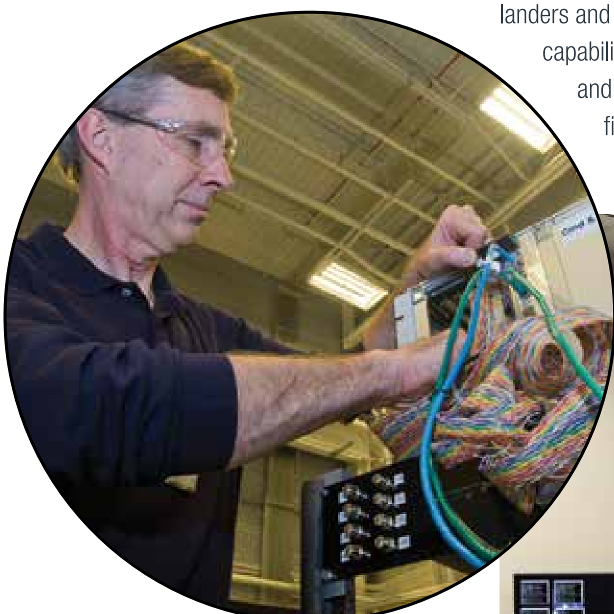
Marshall brings a responsive, agile approach to program and project development efforts. The Marshall flight software team performs the complete range of flight software activities, including requirements development and analysis, software processes and planning, design and development, systems integration, and development testing. Marshall also provides the facilities for flight software development and testing and software formal verification through the development and management of test activities.

Marshall was NASA's first field center to achieve CMM Level 3 required for human missions, is an early adopter of UML, uses agile software development techniques, and continually embraces new approaches and tools to be more efficient in software development.

Marshall's expertise in real-time hardware-in-the-loop (HWIL) capabilities complements its software development efforts by enabling the integrated software and avionics hardware systems of launch vehicles to be modeled, simulated, and tested early, before finalizing designs. The modular HWIL approach is easily extensible to multiple types of spacecraft, landers and launch vehicles. Marshall's HWIL capabilities are powerful tools in verifying and validating both development and final designs of integrated hardware and software systems.

At-A-Glance

Flight software is critical to mission success, both in development and execution. For Class A and human missions, it also must meet exceedingly stringent requirements. Marshall's flight software team was the Agency's first to be certified as Capability Maturity Model (CMM) Level 3 (required for Class A and human missions) and an early adopter of agile modular development and industry standards such as Unified Modeling Language (UML). Combining robustness with agility, Marshall has the capability to design flight software for NASA's future flagship science and human exploration missions.



Marshall's Systems Integration Lab conducts HWIL testing to reduce SLS flight software development risk.

Experience from Racks to Rockets

Marshall's flight software development capability integrates hands-on experience in guidance navigation and control, fault management, International Space Station experiments and operational equipment, satellite control systems, and human-rated flight software. This expertise has been applied to a variety of successful missions, including:

Launch Vehicles

- Space Launch System (SLS) Core Stage Command and Control
- Flight imaging launch monitoring real-time system (FILMRS) camera software for SLS
- J-2X Engine
- Ares I Vehicle and Upper Stage Command and Control
- Space Shuttle Main Engine
- Fastrac Engine Ground System

Spacecraft

- FASTSAT
- DARPA Orbital Express
- Advanced Video Guidance Sensor (AVGS)
- GOES Solar X-ray Imager (SXI)

International Space Station

- Materials Science Research Rack (MSRR)
- ECLSS Urine Processor Assembly (UPA)

Scientific Instruments on Balloon, Aircraft and Space Platforms

- High-Energy Replicated Optics to Explore the Sun (HEROES)
- Hurricane Imaging Radiometer (HIRAD)
- MMS Magnetospheric Multiscale Dual Ion Sensors
- Mighty Eagle Lander Demonstrator
- Sounding rockets

Testing In-Space Software Performance on Earth

To quickly and effectively meet the needs of any project, Marshall has developed state-of-the-art tools, facilities, and test environments. These facilities support the development, test, integration, and verification of mission-critical human-rated embedded flight software for both small projects and large complex space systems.

Real-Time Hardware-in-the-Loop Integrated Test Laboratories
Marshall is home to two real-time hardware-in-the-loop simulation labs. The Systems Integration Lab (SIL) demonstrates real-time flight control of a launch vehicle, such as SLS, during ascent. The Software Integration and Test Facility (SITF) integrates and tests software specifically for the SLS Core/Upper Stage avionics system. Modular in design, both facilities quickly adapt to changing configurations to accommodate incremental integration and testing and fault injection. The SIL and SITF accommodate a variety of software and avionics configurations and integrated simulations for launch vehicle and spacecraft projects.

Software engineers in the SITF use custom tools like ARTEMIS and MAESTRO to test flight software for various avionics configurations to ensure performance.

Specialized Software Tools for Simulation and Testing

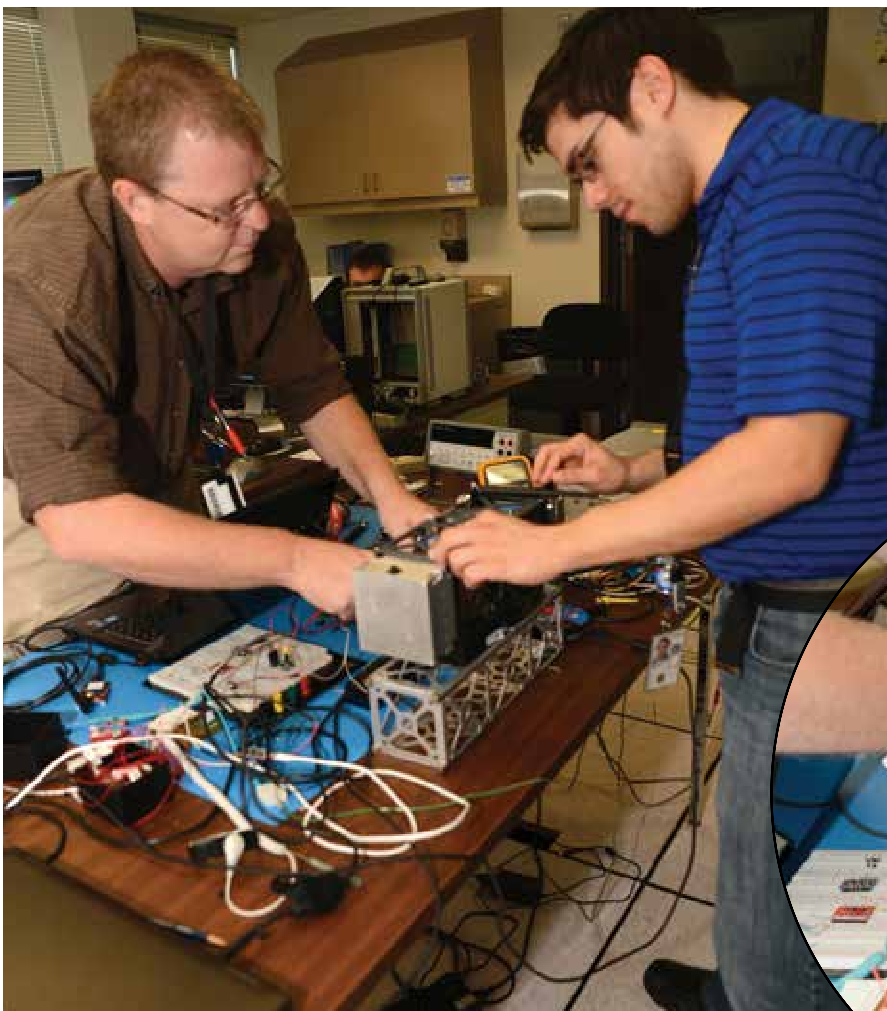
Both the SIL and SITF are equipped with Marshall's highly specialized software tools, ARTEMIS and MAESTRO.

- A Real-Time Environment for Modeling, Integration, and Simulation (ARTEMIS) is a suite of models, simulations, and hardware interfaces used for simulating avionics hardware/software through all phases of mission from pre-launch through orbit insertion. It includes core simulation, subsystem models, component models, and input/output hardware to communicate with flight-like avionics.
- The Managed Automation Environment for Simulation, Test, and Real-Time Operations (MAESTRO) is an automated laboratory management tool that configures and controls test operations. MAESTRO sets up a test configuration and executes and monitors test scenarios based on that test configuration, and it archives test products for later retrieval and analysis.

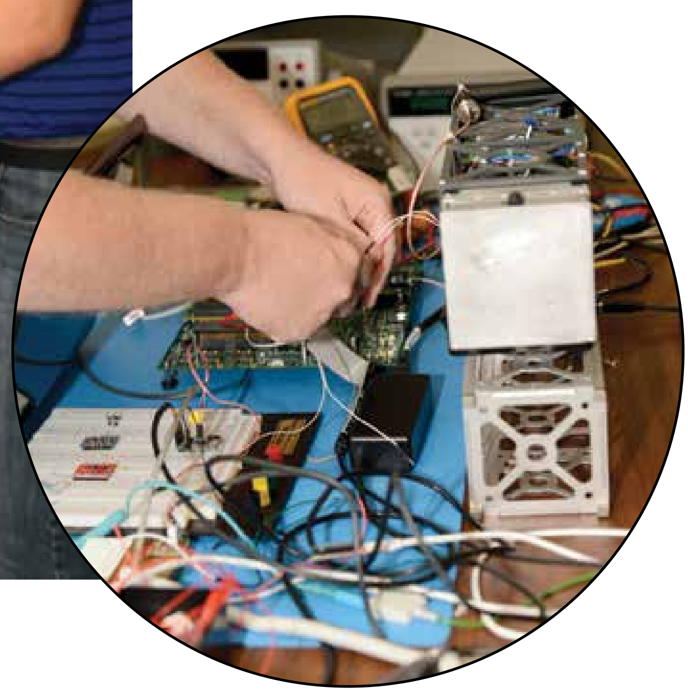
ARTEMIS and MAESTRO are integrated to create real-time launch vehicle simulations for the SLS. The integrated system allows early requirements validation in addition to verification and validation activities before and during hardware development. The modular design supports multiple test configurations across all Marshall HWIL facilities. Marshall is working on open-source versions of ARTEMIS and MAESTRO to support a low-cost generic framework for simulation capabilities.

Small Projects Rapid Integration and Test Environment (SPRITE)

SPRITE is a modular HWIL test facility that provides rapid development, integration, and testing capabilities of flight software for small projects. SPRITE focuses on efficient processes and modular design to support rapid prototyping, integration, testing and verification of small projects at an affordable cost. In addition, Marshall is developing the Low Cost Software Platform (LocSwap), a spinoff from SPRITE, as an open-source tool for industry.



SPRITE provides affordable risk reduction for smaller projects via agile development and modular design.



Fast, First Release of SLS Software

NASA engineers working on the new Space Launch System delivered the first release of flight software in May 2013, three weeks ahead of schedule, by using the Boeing-provided test bed flight computers. As the SLS program pursues its aggressive schedule toward a first flight in 2017, flight software development is a critical aspect of the integrated system, requiring the highest standards and robustness of Class A and human missions.

Availability of this test bed platform early in the engineering development phase allowed Marshall to reduce technical and schedule risk to help the program meet development milestones, as well as to allow more time for Marshall programmers to continue development of what will be the most capable flight software in the history of spaceflight.

Key objectives for this initial flight software delivery included implementation of key flight software infrastructure functionality and the ability to communicate across the vehicle's flight-critical data busses. This flight software release will support Boeing's Avionics Integration Laboratory testing, as well as future planned Michoud Assembly Facility testing. Additional functionality will be added to each release to support the progress in test and integration phases.

Fine-tuning of the software is underway, and ultimately it will be installed at Marshall's Software Integration Test Facility and tested with other electrical hardware and software. The SLS team will run a variety of simulations to evaluate how the vehicle will perform in space.

Flight software development is one of the more technically challenging aspects of any complex space system and frequently one of the top schedule risks.

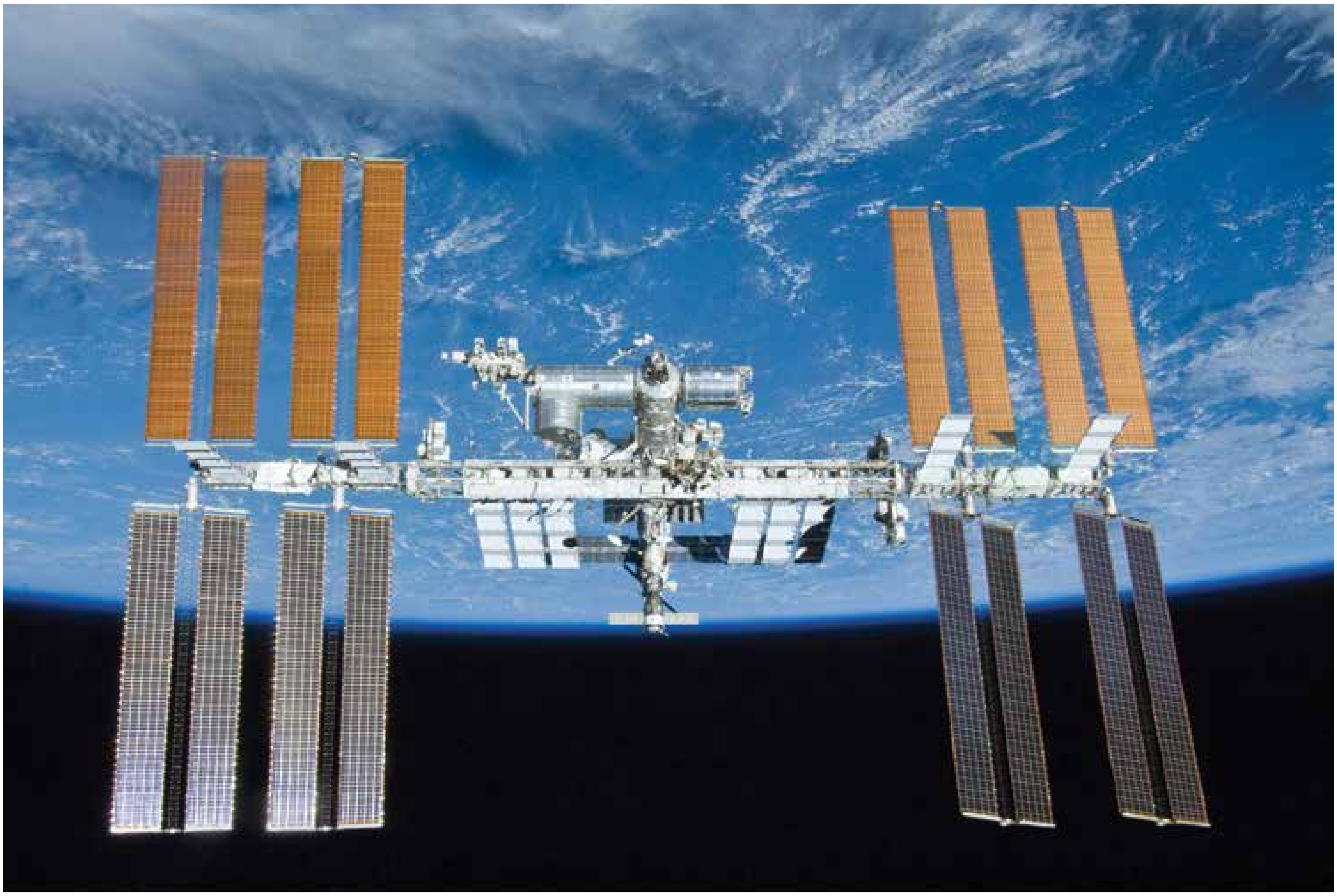
Payload Systems

Proven Processes Reduce Cost and Time

Marshall Space Flight Center has proven processes to design, develop, test, and integrate payloads for on-orbit operations. Programs such as Shuttle and International Space Station (ISS) have very stringent verification requirements, and Marshall has matured its capability to meet these requirements consistently. As a result, sole verification responsibilities have routinely been delegated to the Center. Because of the Center's engineering and systems integration expertise and understanding of customer requirements and environmental conditions, Marshall's validation, verification, and flight certification processes are well regarded. Because Marshall's processes have been optimized internally, verification and validation tests are performed efficiently, resulting in schedule savings. Flight opportunities are limited and often scheduled years in advance. Missing a window for the next launch vehicle can be costly, but because Marshall payloads do not require additional testing at the program level, there are additional schedule savings.

At-A-Glance

Marshall has a rich heritage in the development and testing of payloads, racks, systems, and components. The Center's reliable and demonstrated processes result in efficient payload delivery and successful teaming with international partners, academia, other NASA centers, and industry. Marshall's expertise and unique facilities serve as a conduit for reliable and effective advancement of payload development and demonstration.



Unique human spaceflight safety requirements have led to implementation of rigorous Marshall safety processes and requirements. Each project has a safety engineer matrixed to the team. Payloads are taken through a process of very robust requirements. Marshall develops and integrates safety data packages, which are presented for review and approval by multilevel boards following a governance process.

Marshall also performs end-to-end tests allowing earlier identification of problems and time for the payload team to correct issues before on-orbit operations. Crew time is extremely expensive and limited, so effective ground-based troubleshooting is critical.

Expertise with On-Orbit Research Facilities

Marshall has a deep heritage in engineering and payload management that dates back to Skylab and Spacelab. The Center designs, develops, manufactures, tests, operates, manages projects, and interfaces with the customer organization. Because of Marshall's role in developing and operating these facilities, the Center offers unique insight and expertise to payload developers who need to integrate with them on-orbit.

Marshall's test suite is connected to the Huntsville Operations Support Center (HOSC) for full software verification and validation checkout. Marshall is the only center that provides this unique capability to the Agency, enabling true end-to-end testing of payload telemetry.

Marshall's expertise is demonstrated and enriched by its ISS research facilities, such as the EXPRESS suite of racks, Microgravity Science Glovebox, and the Material Science Research Rack-1. The Center's development and operation of these facilities allows insight and expert integration of systems and processes required to deliver on-orbit payloads. The EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) Rack is a standardized payload rack system that transports, stores, and supports experiments aboard the ISS. It was developed specifically to maximize the station's research capabilities by providing small payloads with a shortened integration time. With its standardized hardware interfaces and streamlined approach, the EXPRESS Rack enables quick, simple integration of multiple payloads aboard the ISS, resulting in easier and more affordable delivery of payloads.

The Microgravity Science Glovebox (MSG) enables scientists from multiple disciplines to participate actively in the assembly and operation of experiments in space with much the same degree of involvement they have in their own research laboratories. Developed by the European Space Agency (ESA) and managed by Marshall, the MSG was launched to the ISS in June 2002. This facility offers an enclosed 255-liter (9-cubic-foot) work area accessible to the crew through glove ports and to ground-based scientists through real-time data links and video. Because the work area is sealed and held at a negative pressure, the crew can manipulate experiment hardware and samples without the danger of small parts, particulates, fluids, or gasses escaping into the open laboratory module.

EXPRESS allows rapid integration of multiple payloads, streamlining payload operations.

The Material Science Research Rack-1 (MSRR-1) is an International Standard Payload Rack outfitted with custom-designed subsystems to provide ground controllers or the onboard crew with the capability to monitor and control high-temperature material research. Marshall designed and developed the subsystems to accommodate the operations of the MSRR. Marshall also performed the hardware/software integration, testing, and verification necessary to certify the facility for flight.

Stand-Out Facilities

The Space Systems Integration and Test Facility is a unique multipurpose facility that enables the design and development of space systems from proof-of-concept studies, prototype and development hardware check-out, integration and assembly of flight systems, and qualification and acceptance testing of components, subsystems, and integrated systems through real-time operations of on-orbit payloads. To implement these functions, the facility incorporates a 10,000-square-foot temperature- and humidity-controlled high-bay work area. The high bay is fully equipped for handling flight hardware.

A Payload Rack Checkout Unit (PRCU) is used for verification and validation of ISS-class payloads and sub-rack payloads. The PRCU, located in the Space Systems Integration & Test Facility, provides a high-fidelity emulation of ISS resources including command and data handling, power, cooling, video, vacuum, and gas distribution.

Marshall's custom-designed MSRR subsystems enable users to conduct high-temperature materials experiments on ISS.

3-D Payload Will Reduce Future Payload Costs

Marshall has joined with Made in Space, a Moffett Field, California, company, to develop and test a 3-D printer that will build tools on the ISS. The 3-D Printing in Zero-G Technology Demonstration payload will perform the first-ever 3-D printing on the space station platform to begin changing the current model for resupply and repair to one that is more suitable for all exploration missions.

Marshall's role is to guide the design process and conduct all of the reviews for the experiment, including project design and critical design, and the environmental and qualification testing to ensure that the hardware is flight certified. Testing is being conducted at various Marshall facilities.

The 3-D Print technology demonstration payload will use extrusion additive manufacturing that builds objects, layer-by-layer, out of polymers and other materials. The first practical applications for the printer payload include certain kinds of widgets, everyday parts like spacers for drawers or shelves. The print-on-demand capability removes any logistical considerations, such as planning for storage or accounting for the mass in payload calculations.

The 3-D printing payload could also spare astronauts from having to wait for replacement parts. At $10,000 per pound, shuttling cargo into space is extremely expensive and slow, with six months or more before new supplies can be brought to the station. It will allow crew members to make some objects in less than an hour. This will speed up development time, accelerate the innovation cycle, and increase the safety of space missions. By increasing reliability on what the crew can build themselves, NASA will also decrease its reliance on commercial payload launch schedules, saving a considerable amount of money.

Marshall supported Made In Space in certifying their 3-D printer for installation on the ISS.

Mission Operations

Success in Space Starts on the Ground

Space research and exploration are increasingly becoming an international collaborative venture. Marshall applies five decades of experience in mission operations to provide turnkey solutions with operations services including payload planning and training and distributed services to remote customers around the globe. Marshall continually advances its capabilities to enhance existing programs such as the ISS and to pave the way for mission operations for future exploration programs.

Marshall is responsible for sustaining ground services to operate ISS payloads and supports preparations to operate the Space Launch System (SLS). Marshall's skilled workforce has resources to define, develop, validate, and train for operating space-based systems and plays a key role in the command and control of the world's most advanced space systems. From ISS payloads and launch vehicles to Earth-orbiting satellites and deep space explorers, Marshall's mission operations capabilities assist users in enhancing the operability of assets.

At-A-Glance

Marshall Space Flight Center applies decades of experience with both customers and hardware to continually advance mission operations capabilities for science and exploration missions. As proven by Marshall's management of the International Space Station (ISS) science operations, the Center explores the implementation of the latest trends and capabilities to continually improve service. The Center's emphasis on customer-focused solutions and international collaboration, in addition to extensive expertise and services, is the foundation for successful mission operations.

Marshall mission operations support provides integrated verification testing with payload rack systems.

Accelerating Space Station Science

The Payload Operations Integration Center (POIC), located within the HOSC at Marshall, is the primary NASA ground system responsible for integrated operational payload flight control and planning for the ISS. It provides payload telemetry processing, command uplink, and planning capabilities for a large number of local Cadre flight controllers and remote ISS payload users and other facilities located throughout the world. The POIC provides a secure integration point for planning all ISS operations.

NASA recently upgraded the POIC payload operations control room with new capabilities to enhance collaboration and efficiency. Based on Marshall's lessons learned from years of ISS operations and with a user-focused approach, the Center redesigned the control room and upgraded to modern equipment.

The renovated control room features a video wall that allows multiple data and video views related to experiments to be shared by the full team. The upgraded flight control room's new arrangement of flight control positions also improves team communication.

Marshall's upgraded POIC enhances ISS work by planning and coordinating all the research activities on the station. The POIC, integral in making the ISS fully functional, is now allowing crews to make more efficient use of time for scientific research, benefiting space exploration as well as life on Earth.

Marshall coordinates experiments, synchronizes payload activities of international partners, and directs communications between researchers and their experiments.

Focus on Users

Marshall provides a wide array of mission operations services and serves a large number of programs. The Center is highly connected with user and mission communities, including international partners. Marshall has strong relationships with users and provides program customers with advanced solution customization and scalability. Services are routinely tailored to meet specific needs — full customer-driven solutions can be provided as well as full-mission operations capability for command and control, mission design, and implementation. The Marshall team puts user needs first and emphasizes users' control of their mission objectives and space activities.

Advancing the Operability of Space Assets

Marshall mission operations is continually advancing and upgrading capabilities to better serve users and adapt to advances in space operations and exploration. Whether it is an ISS payload, a launch vehicle, an Earth-orbiting satellite, or a deep space explorer, advanced capabilities at Marshall assist users in enhancing the operability of their systems; planning mission operations; training astronauts and users; and rapidly deploying and configuring ground-based command and data systems, mission operations personnel, and mission design capabilities to ensure mission success.

Autonomous Mission Operations (AMO) is on the horizon, focusing on ways to reduce crew dependence on ground-based mission control.

The Virtual Training Unit (VTU) glassrack — a new function for mission operations — provides a rapid and cost-effective environment for creating an ISS payload basic trainer for ground support personnel and astronauts. It also provides a prototyping environment for evaluation of human interfaces for ISS payloads in development.

Disruption Tolerant Networking (DTN) is a new networking technology that is being tested on the ISS. DTN will enable NASA and other space agencies around the world to better communicate with international spacecraft that will be used in future exploration. This technology is evolving into an interplanetary internet.

Current Users and Services

	User Services	Mission Implementation	Data Services
SLS	• Training and simulations • Mission planning	• Supportability engineering • Operability • Operations cost analysis • Discrete event simulation • Ground and on-orbit logistics • Ground support equipment engineering	• Ground data system design • Space network interface connectivity
ISS	• Training and simulations • Mission planning	• On-orbit logistics • Mission command and control research activities	• Ground data system design • Space network interface connectivity • Data flow management
AES	• Training and simulations • Mission planning	• Operability • Mission command and control research activities	• Ground data system design • Space network interface connectivity • Data flow management
Others (Agency, universities, industry, DOD/ DARPA)	• Training and simulations • Mission design • Mission planning	• Supportability engineering • Operability • Operations cost analysis • Discrete event simulation • Ground and on-orbit logistics • Ground support equipment engineering • Mission command and control	• Ground data system design • Space network interface connectivity • Data flow management

Experience and Expertise

Marshall has a deep heritage in providing both space-based and ground-based mission operations capabilities for NASA and the international science community, including the Apollo Program, Skylab, Shuttle/Spacelab, and ISS. In addition to its ISS operations role, the Center manages multiple science facilities that house ISS experiments and the environmental control and life support system that enables humans to live onboard.

Marshall designs and implements custom mission operations systems and support for NASA, DOD, and industry partners. The Center provides interfaces for command and control of space missions. Marshall offers users a broad range of expertise and services including:

- Mission Operations Laboratory, expert training of astronauts and ground controllers
- Ground systems including telemetry, voice, video, information management, data reduction, and payload planning, linking scientists with their experiments
- Huntsville Operations Support Center (HOSC), supporting launches, monitoring a range of propulsion parameters
- Engineering support systems for launch vehicles (Redstone, Atlas, Saturn, shuttle, SLS, Hubble Space Telescope, HEAO, Chandra)
- Mission design for manned and unmanned spacecraft (Spacelab, ISS, HEAO, FASTSAT, and Chandra)
- Science Operations Planning and Execution for manned and unmanned missions (Spacelab, Chandra, ISS, FASTSAT)
- Ground support equipment system engineering and supportability engineering

Exclusive Resources/Facilities

Marshall has extensive mission operations experience in a wide range of operations and ground systems interface disciplines. A varied and extensive network of facilities, tools, and capabilities is available to meet the needs of mission operations customers. These unique resources/facilities include:

- **Systems**: Telescience Resource Kit (TReK)
- **Facilities**: Huntsville Operations Support Center (HOSC)
- **Laboratory Training Complex (LTC)**: VTU glassrack that provides a rapid and cost-effective environment for creating an ISS payload basic trainer for ground support personnel and astronauts
- **Payload Operations Integration Center (POIC)**.

Life Support Systems Design and Development

Robust Life Support for Human Exploration of Space

Life support is foundational to human exploration of the solar system, whether during launch, on orbit in the ISS, or beyond Earth orbit. As Marshall partners pursue the ultimate goal of fully closed-loop, regenerative, integrated air/water life systems, the Center is also focused on reducing system complexity and emphasizing precision assembly to improve the reliability of future systems.

Marshall has the infrastructure in place to support life-support systems capabilities — from chemical laboratories and machine shops to environmentally controlled flight hardware testing laboratories and simulators for future mission hardware testing. The unique facilities, along with extensive experience and expertise, advance technology capabilities for future human space missions as well as follow-on spinoff applications on Earth.

At-A-Glance

To extend the International Space Station (ISS) and for future exploration missions to reach beyond low Earth orbit (LEO), environmental control and life support systems require improving cost, mass, and efficient technical assembly of future systems. Marshall Space Flight Center leverages its expertise in life support systems and close collaboration with research and industry partners to advance toward a goal of fully closed-loop, regenerative, and integrated air/water life support systems.

Spinoff Technology

While the ISS environmental life support system makes it possible to live in space and is essential for future exploration, the technologies developed have resulted in practical, tangible benefits on Earth.

Advanced Bosch CO2 technology leads to reduced climate threat and increased brick strength

Learning how to homestead Mars is also helping Marshall and commercial partners develop techniques to reduce CO_2 emissions on Earth. Studies have shown that the presence of well-dispersed carbon nanofibers or nanotubes in cement results in concrete with dramatically improved material characteristics. That knowledge combined with Marshall's experience with Bosch-based life support CO_2 technology will enable long-duration missions to recover 100 percent of the oxygen from metabolic CO_2.

Regolith could also be used in 3-D printing materials to support a Mars base. Rather than releasing carbon produced in the process, the new approach incorporates carbon as nanotubes and fibers that strengthen the bricks. Using an in situ catalyst for life support and re-using the materials to further support base construction and operations, will greatly reduce supply and resupply needed from Earth.

While advancing the Bosch process for exploration, Marshall is partnering with companies in the cement industry, currently the fourth-ranked global emitter of CO_2. Capturing carbon and incorporating it into the cement product would help reduce a climate threat while improving brick tensile strength.

The Atmosphere Revitalization Recovery and Environmental Monitoring project is advancing current state-of-the art CO2 removal systems.

Adsorbent coating technology benefits trace contaminant control

Today, the ISS refreshes the cabin atmosphere by using physical adsorbent pellets to remove CO_2 at room temperature and pressure and then release it when exposed to a higher temperature and the vacuum of space. However, dust from the adsorbent pellets presents challenges.

NASA, industry, and academic partners are testing alternative approaches to prevent dust release, such as coating adsorbent materials onto a microscopic metal lattice, leading to a more robust CO_2 removal process design. This adsorbent coating has spinoff benefits for trace contaminant control and water vapor removal.

Water reclamation supports worldwide water purification efforts

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By efficiently recycling wastewater aboard the space station, the need to resupply water is reduced. A component of the ISS regenerative environmental control life support system is the Water Recovery System (WRS), which conducts the water purification and filtration process. Commercial companies have adapted the WRS to an Earth-based water treatment system. The commercialization of this station-related technology has provided aid and disaster relief for communities worldwide.

Extending ISS Life Support Systems

Marshall designs, constructs, and tests regenerative life support hardware for the ISS. For example, before its 2008 launch, the Water Recovery System (WRS) and Oxygen Generation System (OGS) in the station's U.S. segments underwent extensive design, development, and testing on the ground at Marshall and in space.

The ISS WRS and OGS have each recycled more mass in consumables than sent to orbit.

	Mass Reduction to Mass Launched (lbs)
WRS	5:1
OGS	2.6:1

Potentially higher mass-based ROIs that will enable and enhance long-duration human missions beyond LEO will require reductions in both the initial system masses and their recurring mass replacement rates. The basic challenge with reducing initial system mass is to develop smaller and lighter equipment that can provide the same level of performance and functionality as is provided by today's state-of-the-art equipment. Marshall is addressing this by reducing recurring mass to develop longer-life equipment that is not expended as it operates (e.g., filters) and that is less prone to failure.

Marshall's extensive systems development and integration expertise, spanning all phases of the station's environmental control and life support life cycle, will allow the Center to continue major roles to evolve state-of-the-art environmental control and life support systems and technologies meeting NASA strategic priorities (high reliability, reduced logistics, higher efficiencies, etc.) for human exploration.

Enabling Future Human Exploration Missions

A challenge for life support systems is "closing the loop," for evolving advanced technologies that convert human waste into pure consumables. These will reduce the costs of supplying permanent operations in Earth orbit and enable missions deep into the solar system.

Today's ISS life support system recycles about 88 percent of the wastewater and 50 percent of the oxygen. The balance is lost and must be replenished from Earth. Marshall and its partners are evaluating new catalyst materials and techniques to develop a highly reliable, robust integrated air/water system. This work builds on two established chemical processes, Sabatier, converting hydrogen and CO2 into methane and water, and Bosch process, converting CO2 and hydrogen into carbon and water.

Marshall's module simulators allow testing of future environmental life support systems.

Marshall leverages its deep expertise in these kinds of systems and its close collaboration with research and industry production partners to combine air and water into an integrated, closed-loop, regenerative system.

Unique Facilities

Marshall's ECLSS Test Facility allows side-by-side testing for quantitative, objective comparisons. Support services include distributed control/data acquisition systems interfaced to a centralized data archiving system, a chemistry laboratory, a machine shop, and an environmentally controlled room for flight hardware testing.

ECLSS system engineers and scientists on the ground can troubleshoot any problems encountered in space. Examples include:

- Bench-top, assembly, subsystem, and system tests to determine performance and reliability and to assess alternative ECLSS architectural approaches
- Operational tests using volunteers in daily activities such as exercise and showering to generate wastewater for reuse
- Qualification and acceptance tests of flight hardware for the space station

In future mission profiles, astronauts are expected to live in modules below standard sea-level pressure, but with the equivalent oxygen level, to reduce spacecraft mass. Marshall has two module simulators, the Exploration Test Chamber (E-Chamber) and the Vacuum Test Chamber (V-Chamber), to mimic that living environment to test future ECLSS hardware

Environmental Test

Customized Tests To Meet Challenging Schedules

Marshall Space Flight Center customizes tests with a demonstrated ability to rapidly adapt and reconfigure systems to meet customers' needs by applying the broad experience and variety of test systems, facilities, and equipment available.

Understanding the effects of the space environment on materials, structures, and systems is fundamental and essential to mission success. If not correctly comprehended and designed for, the effects of the space environment can lead to degradation of materials, reduction of functional lifetime, and system failure.

The environmental test systems, facilities, and equipment combined with capabilities such as nondestructive evaluation, failure analysis, and mechanical testing make Marshall a one-stop shop for materials and flight hardware analysis.

The Discipline of Test Engineering

Experience with many classes of test applications (launch, ground environment, propulsion, in-space, crew cabin) gives Marshall exceptional versatility in defining the right test for the right application. The Center's comprehensive environmental test capabilities support a range of organizations, including NASA, other government agencies/entities, commercial customers, and academia. These capabilities are maintained and operated by highly trained and experienced personnel with a reputation for delivering what the customer needs when the customer needs it.

Capabilities have been used to support projects from many NASA mission directorates such as Chandra, Space Shuttle, James Webb Space

At-A-Glance

Integration and test is one of the most challenging phases of mission development and must be executed adaptively and efficiently to maintain schedule and allow for resolution of issues that threaten mission success. With broad expertise and a wide array of test systems, facilities, and equipment available, Marshall is able to customize tests with a demonstrated ability to rapidly adapt and reconfigure systems to meet customers' needs.

Marshall's expertise in environmental testing ensures that projects get the analysis needed on schedule and within budget.

Telescope, Phoenix, FASTRAC, International Space Station, Space Launch System, and Solar Probe Plus. Other government agencies that have used Marshall's broad spectrum of test capabilities include the Department of Defense, the U.S. Army Aviation and Missile Research Development and Engineering Center, Naval Sea Systems Command, and Naval Air Systems Command.

Commercial customers coming to Marshall include Space Systems/Loral, Aerojet, Ball Aerospace, Emcore, SpaceX, Virgin Galactic, and Sierra Nevada. Academic institutions using the capabilities at Marshall include the University of Delaware, the University of Mississippi, and Johns Hopkins University Applied Physics Laboratory.

One-Stop-Shop Expertise

The broad range of environmental test capabilities at Marshall offers programs the ability to develop and implement stringent customized tests along with expert results analysis. From piecemeal or end-to-end/comprehensive tests and analysis, the Center offers one location to cover almost any test need.

Marshall's Environmental Test Facility (ETF) provides various environments allowing a customer to test and qualify hardware prior to launch. The environments include the vacuum environment of space, the in-cabin environment of spacecraft, and the natural environment seen by a vehicle on the pad prior to launch.

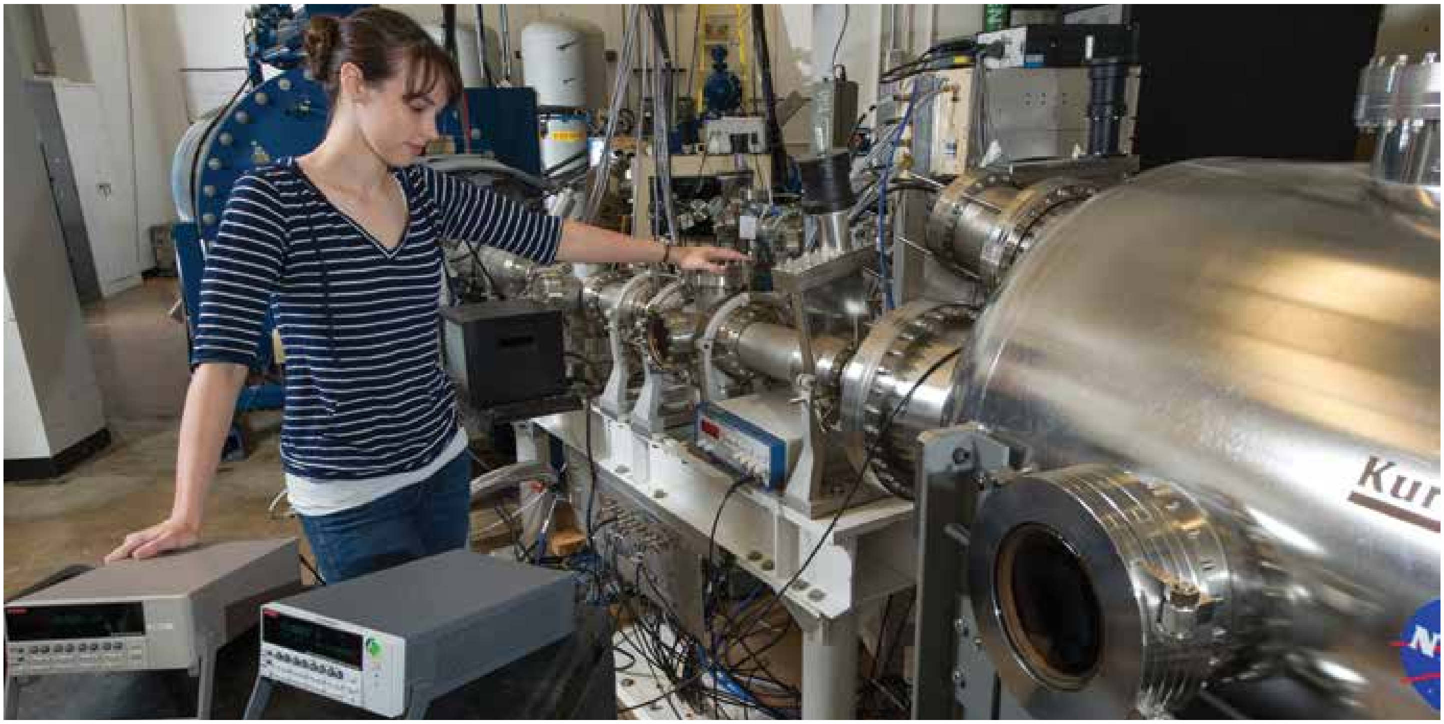
The Aerodynamic Research Facility (ARF) provides a low-cost test alternative relative to much larger wind tunnel facilities for early database development of aerospace systems, such as SLS. It also supports the entire agency as well as outside commercial and DOD customers. Other available testing capabilities include:

- Life cycle
- Launch simulation
- Thermal-humidity-altitude
- Charged particle radiation
- Ultraviolet radiation
- Vacuum outgassing
- Atomic oxygen
- Plasma interactions
- Planetary and extraterrestrial environments
- Impact testing

The aggregation of space environmental test capabilities at Marshall is a comprehensive set allowing for simultaneous exposures of multiple space environments.

Many are capable of conducting classified tests. The engineers, scientists, and technicians working in and running these facilities are award-winning, nationally recognized experts in their respective fields and have a proven record of dealing with contingencies to maintain mission success.

XRCF tested JWST mirrors to validate performance in extreme space environments.



The Pelletron particle accelerator exposes test articles to the simulated radiation conditions of space.

Resources To Develop and Conduct Tests Essential to Mission Success

Marshall's X-ray and Cryogenic Facility (XRCF) is a unique optical, cryogenic, and X-ray vacuum test facility. The vacuum chamber is a horizontal cylinder, 20 feet in diameter and 65 feet long, that is capable of achieving temperatures from 20 Kelvin to 160 F and vacuum levels less than 10-6 Torr. The chamber has liquid nitrogen panels and heater panels to simulate deep space environments and to maintain accurate thermal stability. Tests performed at XRCF are crucial to mission success, such as those performed on the James Webb Telescope to ensure that the mirrors and components will be able to withstand the extreme cold temperatures of space.

The Pelletron Combined Environmental Effects Facility irradiates materials with simultaneous exposures. The Solar Wind Test Facility exposes materials to low-energy protons, low-energy electrons, and ultraviolet radiation concurrently.

Marshall's micro light gas gun (MLGG) is capable of accelerating small particles to velocities of 20 km/sec to quantify micrometeoroid and orbital debris. It is the only functional one of its kind in the United States. Micrometeoroids and space debris can puncture manned spacecraft, pit windows and telescope mirrors, and damage solar arrays and thermal radiators. Marshall's MLGG can quantify the damage caused by debris particles or qualify debris protection systems. It has been used to study debris impact effects for the International Space Station.

The Hydrometeor Impact Gun is used by the Department of Defense for its weather encounter testing and evaluation. It is the only hydrometeor gun of its type in the country. It can provide rain impact performance data with a defined single droplet size.

The Lunar Environments Test System (LETS) is the first and only operational test system to examine the lunar surface environment, including dust/regolith effects. LETS was designed to address lunar environment effects on materials and systems as well as to enable study of the effect of lunar dust charging on materials and mechanisms.

The Inducer Test Loop and the Pump Test Equipment facilities are the only water flow test facilities in the agency. The Turbine Test Equipment is a blowdown air facility with a much larger scale and wider operating range than any existing shock tube facility in the United States.

High Intensity Solar Environment Test System (HISET)

Flexible, Customizable Test Solutions

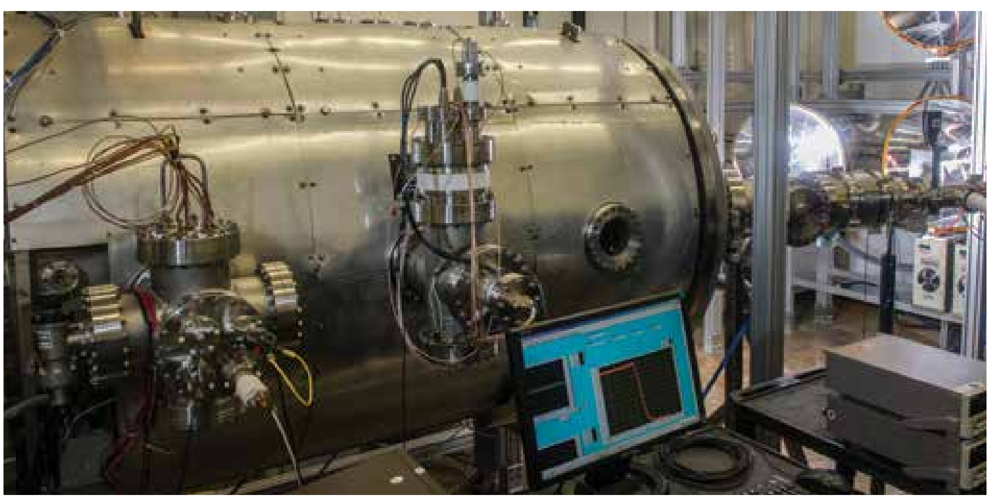
Bringing together elements of the solar space environment — including charged particles and concentrated sunlight — the High-Intensity Solar Environment Test system is an innovative test platform designed to meet a wide range of testing challenges from spacecraft instrument qualification to high-temperature terrestrial materials development. Designed for maximum flexibility, HISET offers customizable solutions from single environment focused test conditions to complex combined environments.

Featuring an impressive 18,000-watt solar light radiation source, HISET offers product and instrument developers a means of testing at temperatures as high as 1,000 C. The solar simulator radiation source is composed of three individual light sources that offer exceptional configurability from single source operation at low power to all sources operating at full power. Capable of being focused into a vacuum chamber, the solar simulator output can be concentrated to a spot as small as 10 centimeters in diameter or expanded to 1 meter in diameter. In addition, HISET can accommodate solar simulator testing in ambient pressure conditions to facilitate systems tests of terrestrial products — from concentrator solar arrays to automotive materials and coatings.

When the solar simulator is coupled to the solar wind environment systems, a completely unique capability is formed. Encompassing a wide range of energy and flux conditions, the solar wind systems provide charged particles (protons and electrons) that cover mission environments from Mercury to Saturn and everything in between. By employing the integrated cryogenic shroud in the vacuum chamber, it is possible to seamlessly test materials and systems from 100 C to +1,000 C.

Solar Probe Plus, a planned mission designed to explore space weather is being tested in HISET. Testing has included aiming a beam of proton particles at the instrument and measuring its response. In order to control the beam location, a system of Helmholtz coils has been arranged to produce a region of nearly zero magnetic field, nullifying the effects of Earth's magnetism. That allows the test particle beam at any energy level to be precisely aimed and moved around on the instrument.

Equipped with a suite of computer data acquisition and diagnostic systems, HISET is poised to meet the needs of the most demanding test applications. It is built for spacecraft systems engineers, science instrument developers, thermal system designers, and materials scientists. Tests of particle instruments, heat pipes, solar power systems, radiators, high-temperature materials, and solar sails are but a few of its potential applications. Created to help advance technology development for both space and terrestrial customers, HISET stands ready to meet the most extreme test requirements.



HISET can be rapidly reconfigured for testing a wide range of solar environmental conditions.

Space Weather and Natural Environments

Expert Design and Decision Support

Ensuring the robustness and reliability of systems in the extreme environments of space, whether for commercial or exploration applications, is a key challenge to mission success. Marshall's repository of space environment effects data is unique in the world, with engineers that have access to a range of test capabilities to support the design of new missions. Data is freely available to industry, partnerships are routinely formed offering test and consulting services, and other agencies frequently collaborate with Marshall's fundamental researchers in heliophysics to improve space weather forecasting and decision support capabilities.

The loss of spacecraft due to the environment can cost hundreds of millions of dollars. Marshall is home to decades of data captured worldwide to define those environments — from Earth's surface to deep space — and the Center provides the information and expertise it takes to design and fly a successful mission.

Designing for the Harsh Environments of Space

Wind, rain, and lightning in Earth's atmosphere impact launches and returning spacecraft, but the vacuum of space is the harshest environment, with meteoroids, cosmic rays, natural radiation belts, solar energetic particles, plasmas, and solar ultraviolet radiation.

At-A-Glance

Marshall Space Flight Center's capabilities reduce risks for the most challenging missions, whether in low Earth orbit (LEO) or deep space. The Center's capabilities and broad range of experience and expertise are unique in the world.

Marshall's unique expertise in space weather aids hardware designers in reducing risk.

Reducing Risks from Radiation Exposure

Marshall experts study sun-influenced space weather and energetic particle emissions from solar flares and other solar eruptions. They also provide data to environmental test experts who work directly with engineers to understand the material needs for a particular spacecraft and to replicate environments to test effects on those materials. Marshall interprets and analyzes data, such as spacecraft charging and ionizing radiation, to understand the environment and determine risks. This wealth of data is collected and made freely available.

Spacecraft charging, including both surface charging and internal dielectric charging, requires a variety of design mitigation techniques. Electrostatic discharge (ESD) from this charging can have consequences ranging from intermittent anomalous behavior to catastrophic failure. Ionizing radiation causes degradation in spacecraft materials and electronics over time, causing transient current pulses that can change information stored in computer memories, upsetting the operation of sensitive circuits, or even resulting in catastrophic damage and loss of electronic components.

The gap between science and engineering is bridged using measurements to answer specific questions and packaging or modeling the data to ensure that current and future aerospace vehicles are successful. Some of the models developed by Marshall include:

- L2 Charged Particle Environment (L2-CPE) Model evaluates the radiation dose on surface materials of spacecraft in orbit about the Sun-Earth L2 Lagrange point or when passing through distant regions of Earth's magnetotail.
- Chandra Radiation Model (CRM), developed for the Chandra X-ray Observatory program, provides low-energy proton flux for environments along a spacecraft trajectory, including the solar wind and magnetosheath outside Earth's magnetic field, and trapped particle environments within the magnetic field as a function of activity levels.
- A version of the NUMIT (numerical integration) internal charging code evaluates risks for ESD in materials exposed to energetic electron environments. The model has simulated static test environments, screened materials for long-term use in geostationary orbit, and simulated decades of interplanetary space exposure on cryogenic materials.

Marshall collects, develops, and disseminates radiation data required to design, manufacture, and operate more reliable, cost-effective spacecraft. In support of the International Space Station (ISS), the Center provides solar activity forecasts for operations personnel, captures and analyzes data to evaluate ESD risks and hazards to crew performing extravehicular activities (EVA), and provides annual and EVA-specific meteor shower forecasts. The Center also extends this experience to other programs such as the Launch Services Program (LSP). Marshall helps LSP engineering personnel evaluate ionizing radiation and spacecraft charging issues for NASA's unmanned launch vehicles.

Unique Facility Tests the Response of Space Environment Exposure

The Low Energy Electron and Ion Facility (LEEIF) located at Marshall is a joint research venture between NASA and seven research universities. LEEIF can expose spacecraft parts to ion beams of specific energy from specific directions to help calibrate the flight data. In 2012 and 2013, teams calibrated the Dual Ion Spectrometer flight sensors for the Magnetospheric Multiscale (MMS) mission planned in 2014. LEEIF is available for calibrating science instruments and is home to a large vacuum chamber for simulating space plasma.

Engineers at LEEIF calibrate instruments for testing in simulated space plasma environments.

Micrometeoroids and Orbital Debris Mitigation

Spacecraft in LEO continually impact with micrometeoroids and with orbital debris (MMOD), which, at high speeds, can cause mechanical or electrical damage. MMOD data transitioning research to applications that benefit space system design and operation increases understanding of the universe and improves space systems.

Modeling:

- Meteoroid Stream Model forecasts meteor showers for Earth and Earth-orbiting spacecraft.
- Meteoroid Engineering Model (MEM) identifies sporadic radiants with real sources of meteoroids, such as comets; uses a physics-based approach to yield accurate fluxes and directionality for interplanetary spacecraft anywhere from .2 AU to 2 AU; and obtains velocity distributions from theory and validates these against observation.

Missions:

- Mars Atmosphere and Volatile EvolutioN (MAVEN) — Marshall experts created models for the MAVEN mission to Mars to help determine risks and mitigation strategies for meteor showers occurring near the potential launch dates.
- Chandra X-ray Observatory — Chandra required a radiation model designed by Marshall to tell operators when to perform science and when to protect X-ray sensors. Marshall personnel also provide custom meteor shower forecasts to aid in operations planning.
- James Webb Space Telescope — Marshall developed the spacecraft charging, surface radiation, and meteoroid environment definitions for the James Webb Space Telescope.

Automated Lunar and Meteor Observatory (ALAMO)

Marshall is home to NASA's Meteoroid Environment Office (MEO) that operates six all-sky camera systems in the southeastern United States and two in New Mexico for the detection of bright meteors and fireballs. ALAMO makes Earth-based telescopic observations of the dark portion of the moon to establish the speed and sizes of large meteoroids (greater than 100 grams) striking the lunar surface.

In addition to the shower meteoroids, the MEO focuses on the sporadic random environment, which is a continuous risk that must be mitigated by appropriate design leading to significant engineering challenges. A designer must determine how much spacecraft shielding is necessary for a spacecraft and what parts of the spacecraft will be most exposed during its mission. The MEO is well known for studying the shower environment, providing forecasts so spacecraft operators can reorient vehicles to point sensitive equipment away from the radiant (direction of origin), skew solar panels edge-on to minimize the cross sectional area presented, and close shutters to protect sensitive optics.

A Prototype To Reduce Risk of Neutron Radiation Exposure

Sending astronauts farther into our solar system than ever before will require advanced instruments designed for monitoring and detecting radiation in space vehicles and habitats. Marshall tackled this problem with a renewed focus on understanding radiation in space environments. Scientists and engineers at Marshall developed a prototype for the Advanced Neutron Spectrometer (ANS) instrument in close collaboration with Johnson Space Center (JSC) and other NASA centers. Marshall developed the prototype instrument in only 11 months. Radioactive sources and exposures to high-energy protons at Indiana University Cyclotron Facility were used to evaluate the performance of the ANS.

The ANS is an instrument designed to monitor neutrons; the aim is to build a new tool to protect astronauts as they explore new destinations. The ANS can be used to detect the levels of radiation in the spacecraft or habitat so that astronauts can employ techniques to minimize their exposure.

By working closely with JSC and other NASA centers, Marshall has been able to make great strides on some key radiation protection issues that include the ANS prototype. The goal is to continue this work to improve the instrument performance and our radiation monitoring capabilities to reduce risks when exploring new destinations.

The MEO provides meteoroid forecasts to reduce risk of mission or spacecraft loss.

Getting There and Back Safely: Ascent, Re-entry, Descent

From launch to landing, Marshall experts have decades of experience in delivering data to increase spacecraft survivability. Marshall models have a wide range of applications, including systems design, performance analysis, operations planning for aerobraking, entry descent and landing, and aerocapture. Models include:

- **Marshall Engineering Thermosphere** (MET) calculates kinetic temperature of the neutrals, number densities of individual species, and total mass density and pressure to help predict atmospheric drag; important to lifetime estimates, orbit determination and tracking, attitude dynamics, and re-entry prediction.
- **Earth Global Reference Atmospheric Model** (Earth-GRAM) provides density, temperature, pressure, winds, and selected atmospheric constituent concentrations, from the surface of Earth to orbital altitudes, as a function of geographic position and time of year.
- **Mars Global Reference Atmospheric Model** (Mars-GRAM) is an engineering-level atmospheric model widely used for diverse mission applications. Mars GRAM outputs include density, temperature, pressure, winds, and selected atmospheric constituents. Applications include systems design, performance analysis, and operations planning for aerobraking, entry descent and landing, and aerocapture.

Support such as defining, collecting, and evaluating data results in risk reduction for even the most challenging missions. Missions supported include:

- **Space shuttle** — During launch countdown, Marshall evaluated the atmospheric conditions that could impact the vehicle's steering commands. Marshall mission-critical personnel were on console in the Huntsville Operations Support Center for all launches.
- **Space Launch System** (SLS) — Marshall is working with the SLS team to define the natural environments the vehicle and the Orion Multi-Purpose Crew Vehicle will encounter. SLS, managed by Marshall for NASA's Human Exploration Office, is scheduled for its first unmanned test launch in late 2017 from Kennedy Space Center (KSC).
- **Mars Science Laboratory** (MSL) — Marshall supported the Jet Propulsion Laboratory using Mars-GRAM to assess the laboratory's landing capabilities, aiding in the landing site selection process as well as the entry, descent, and landing at Gale crater.
- **Orion Multi-Purpose Crew Vehicle** — Marshall data drove the design of the wave pool built for testing Orion ocean splashdowns, which winds and waves can affect.

New Doppler Radar Wind Profiler Will Help Mitigate Launch Risks

Marshall's role in spacecraft survivability starts at the ground, since getting safely through Earth's atmosphere is the first critical step in any space mission.

The Center is looking forward to a new 50-megahertz (MHz) Doppler Radar Wind Profiler (DRWP) that goes online in late 2014 at Kennedy Space Center (KSC) — well before the first launch of the SLS, America's next advanced heavy-lift rocket, now in development at Marshall.

Marshall built a new database of upper air winds over the KSC area by archiving the 12 years of wind profiles from the existing 50-MHz DRWP. This new database is being used in the design of the SLS. In the past, designers and operators relied on upper atmospheric wind measurements from weather balloons. However, balloons cannot capture rapid changes in winds that can be observed by the wind profiler. Data archived from the 50-MHz DRWP reduce uncertainty in the design of a new launch vehicle, such as the SLS, making it safer.

By using archived data from the older DRWP during the design phase and real-time data from the new DRWP on launch day, the SLS and other commercial launch vehicles will have greater safety and reliability when encountering upper atmospheric winds on their way to space.

Optical Systems

A Unique Solution for X-ray Astronomy

Marshall is the sole domestic source for high-energy X-ray full-shell (Wolter Type I) replicated optics and one of only two sources in the world. This method uses electroformed nickel replication (ENR) fabrication to create extremely precise grazing-incidence optics necessary for high-energy observations. Nickel mirror shells are electroformed onto a figured and super-polished aluminum mandrel and then released by differential thermal contraction.

A distinct advantage of the ENR process is that the resulting mirror shells are inherently very stable, which permits good figure accuracy and hence very good angular resolution (image sharpness). Multiple identical copies can be made from a single mandrel for simple repeat fabrication — a significant cost savings over traditional fabrication methods.

Some of the characteristics of the shells created by this method include:

- Resolution as good as 10 arcsec half-power diameter
- Diameters from 2 to 50 centimeters
- Focal lengths from 1 to 10 meters
- Thickness as low as 50 micron
- Bare nickel, gold, iridium or multilayer coatings
- Optics for soft and hard (up to 70 keV) X-rays

At-A-Glance

Space science research involves continually advancing the state of the art in optics technologies, especially in astrophysics where maximizing the efficiency of optical systems (the amount of light collected per unit mass of instrument and spacecraft) is critical to the next generation of missions. The unique thermal and gravity conditions of the space environment also drive specialized optics expertise requirements. Marshall has developed a unique replicated optics process, which will be key to future high performance applications, and the Center has unique expertise in optics related to X-ray applications.

ENR fabrication enables fast, affordable production of X-ray optics for next-generation instruments.

Marshall has seen great success with this process, and a number of instruments flown in recent years have used ENR nested-shell optics for performing high-energy astrophysics and heliophysics observations. As the scientific community begins looking toward the next generation of X-ray telescopes to follow the Chandra X-ray Observatory, this process provides a key enabling technology for next-generation X-ray instruments that can be produced affordably and efficiently.

Solving Unique Problems in Optics and Instrument Development

Marshall's optical systems capability is composed of several functional organizations, with specialists in replicated cylindrical optics manufacturing, traditional optics manufacturing as well as metrology and testing. This team has earned a reputation as the "emergency room" for optical projects that run into technical challenges. The group is known for its ability to solve optical and opto-mechanical issues as well as manufacture custom solutions.

Marshall's optical systems team works closely with the scientific community both at the Center and at institutions around the world to develop optical instruments that enable groundbreaking scientific discovery and advance understanding of the universe. These include:

- Extensive history with optical systems development dating from the Apollo era, with support to major projects from Skylab to the James Webb Space Telescope (JWST)
- Unique capability for replicated optics manufacturing of grazing-incidence optics needed for high-energy astrophysics, X-ray astronomy, and heliophysics

Marshall's expertise in metrology, optical manufacturing, and optical testing is recognized and sought by customers from around the world. Frequently called in to solve tough technical challenges on other projects, the team at Marshall has been instrumental in optical systems design for NASA and the broader scientific community for more than 40 years. The Center's expertise in optical systems attracts customers from other government agencies, academia, and international space organizations.

Enabling Advances in Space-Based Astronomy

Marshall's legacy in optical systems traces its roots to the development of the Apollo Telescope Mount (ATM) on Skylab and the X-ray telescope on the second High Energy Astronomy Observatory (HEAO-2). Since then, Marshall has been involved in development of a broad cross-section of the Agency's optical instruments. Notably, Marshall played a significant role in NASA's Great Observatories, especially in managing the Hubble Space Telescope and in managing the development, flight, current operations, and guest science observer program of the Chandra X-ray Observatory. Most recently, Marshall has supported the testing of the James Webb Space Telescope flight primary mirror segments and primary mirror backplane structural support in the X-ray and Cryogenic Facility (XRCF). Support of JWST by XRCF began in 1999 with testing of structural and optical configuration within the program.

In addition to the Great Observatories, Marshall has supported a broad array of smaller missions, including the High-Resolution Coronal Imager (Hi-C), the Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket, the High-Energy Replicated Optics for Exploring the Sun (HEROES) training mission, and the Russian-led Astronomical Roentgen Telescope – X-ray Concentrator (ART-XC).

Chandra X-ray Observatory

Marshall began work on Chandra in the mid-1970s. Over the course of Chandra's development, the Center refined its core capability in X-ray optical systems design. Marshall oversaw the manufacture, coating, and alignment of Chandra's nested mirrors to unprecedented exactitude, enabling the immense scientific return of this Great Observatory.

High Resolution Coronal Imager (Hi-C)

Hi-C, launched in July 2012 on a NASA sounding rocket, captured the highest-resolution images ever taken of the sun's corona. The instrument, operating in the extreme ultraviolet region of the spectrum, incorporated some of the finest mirrors ever made. Scientists and engineers from Marshall and the Smithsonian Astronomical Observatory worked together to deliver the instrument.

Optical Calibration and Testing

X-ray and Cryogenic Facility (XRCF)

The XRCF is the world's largest optically clean cryogenic and X-ray test facility. Built in 1975 to test and calibrate HEAO-2, the XRCF was extensively modified during 1989–1991 to perform full-scale calibration tests for Chandra. In 1999, the facility was upgraded to perform cryogenic testing. The facility consists of a 1,700-foot-long X-ray guide tube, an instrument chamber, and two clean rooms (Class 1,000 and 10,000). The extremely clean instrument chamber test vacuum has all electrical and fluid interfaces needed for running tests. Cryogenic and vacuum pumps provide typical test pressures of less than 10^{-6} Torr.

The facility has two interferometers for optically measuring structural distortions that occur during cryogenic testing of telescope mirrors. Both interferometer systems offer fast, quantitative surface figure measurement that is relatively insensitive to the effects of vibration. These instruments can detect thermal distortions as small as a few nanometers. More than 30 cryogenic test operations have been completed since 1999, most in support of JWST.

In addition to the large vacuum chamber, the facility has a smaller, more cost-effective cryogenic and cryogenic optical testing chamber for subscale testing of smaller instruments. The helium-cooled chamber achieves test pressures and temperatures comparable to those of the large chamber, but in about one-tenth the time. It uses control and data acquisition systems similar to those of the larger chamber and uses the same interferometer systems. More than 25 cryogenic test operations have been completed in the small chamber since it was commissioned in 2001.

Straylight Test Facility (SLTF)

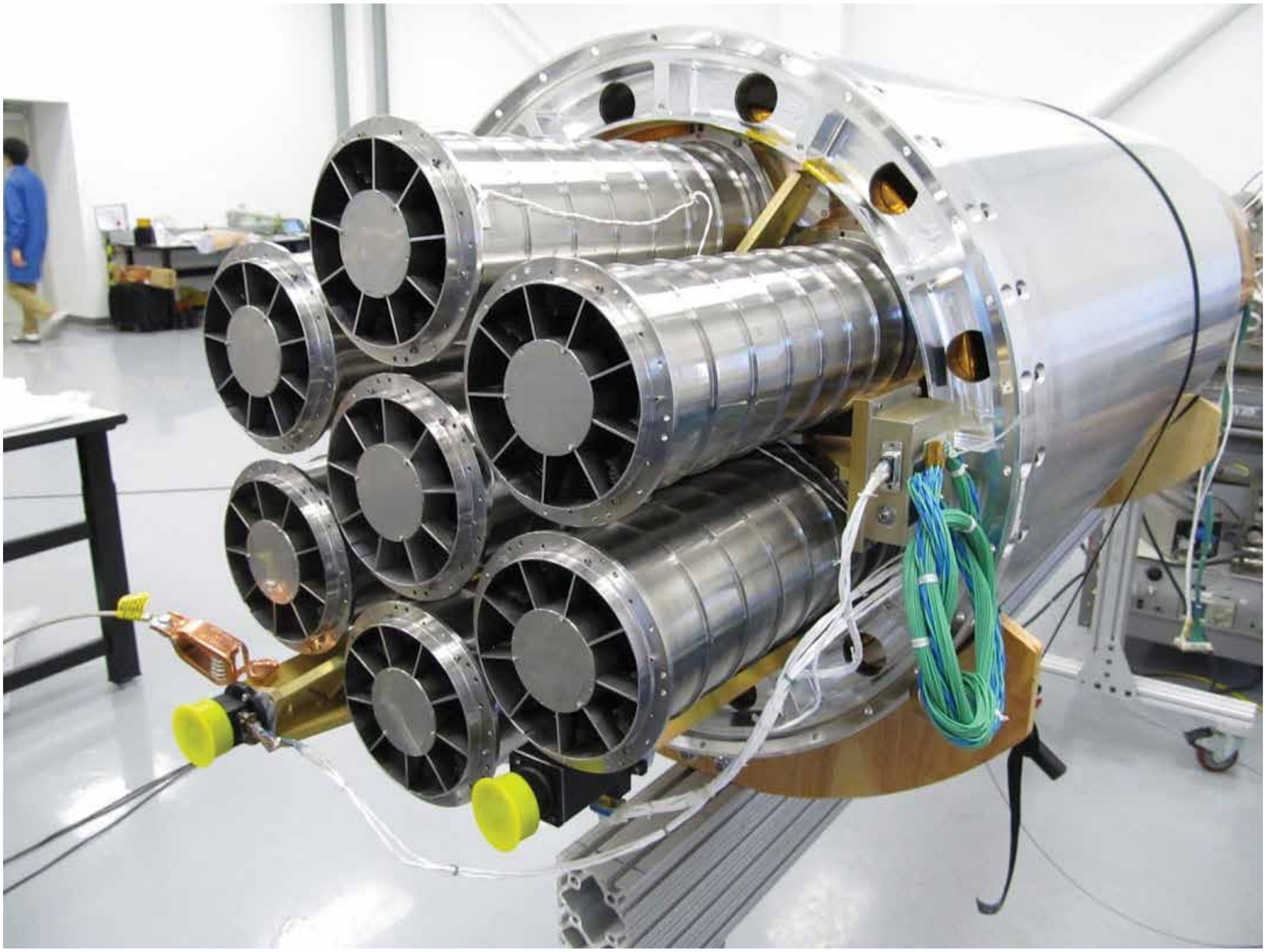
This facility vacuum tests telescope baffle systems to determine whether they meet their performance requirements. A pulsed laser beam shines on the front of the baffle system and the focal plane detects how much light is scattered. The angle of the laser beam varies to any needed angle. The facility can distinguish unwanted stray light from the target's light.

The SLTF is also used as an X-ray test facility with 100-m beam path. X-ray test range is from soft to hard X-rays with mirror sizes to about 1 meter in diameter.

The Straylight Test Facility consists of:

- 3m x 12m test volume for mirror
- 1.3m diameter by 82m long section
- 1.5m diameter by 10m isolatable section
- Pumped with cryopumps; 10-7 torr
- Measure telescope baffle rejection ratios over 15 orders of magnitude

The XRCF supported JWST with cryogenic testing of the flight mirrors and structural components.

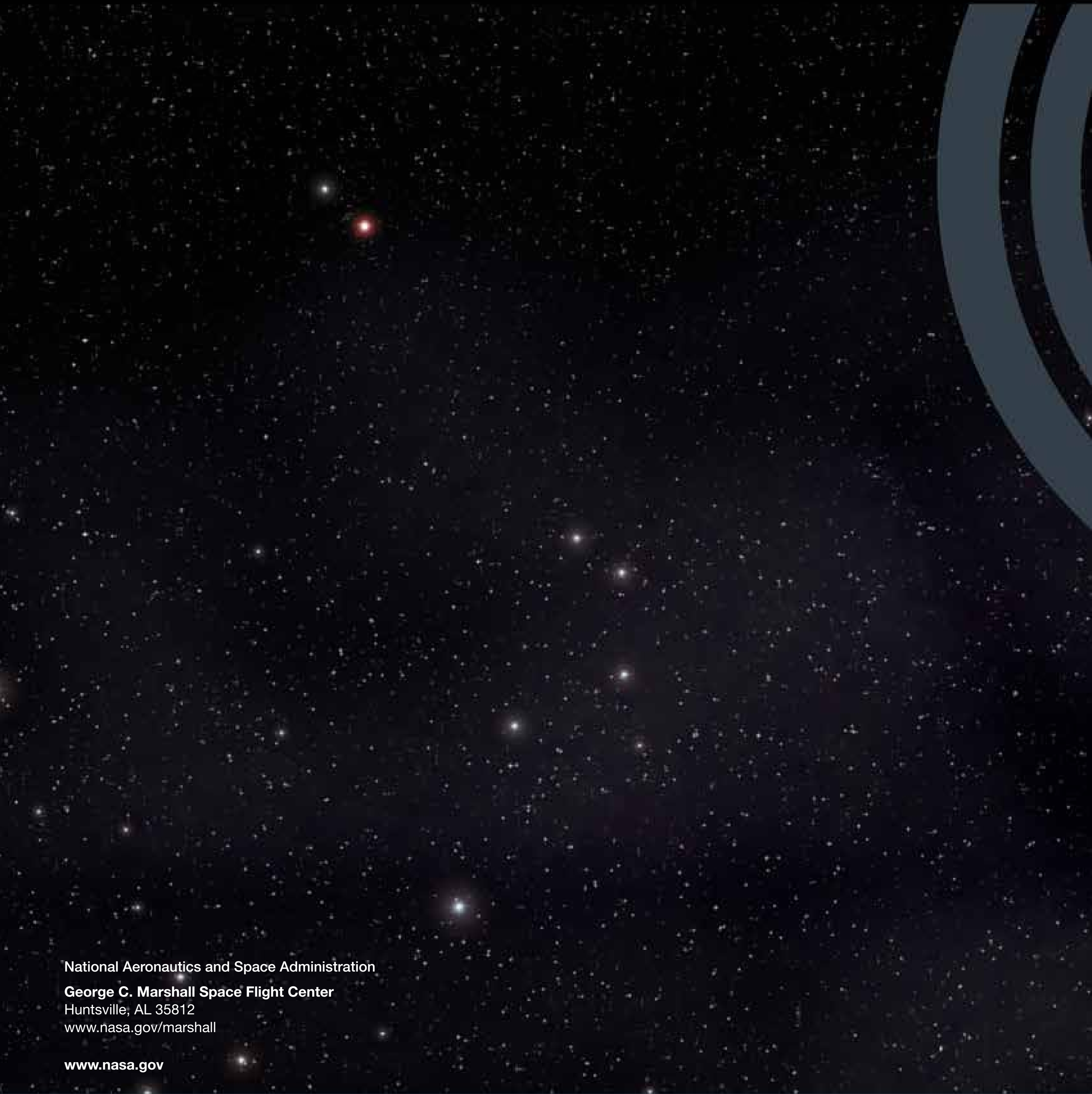


Focusing Optics X-ray Solar Imager (FOXSI)
FOXSI used a set of seven grazing-incidence telescopes developed at Marshall to examine barely visible solar nanoflares at multiple wavelengths. Using the Center's unique replicated optics manufacturing capability, the extremely sensitive and highly reflective optics were designed at significantly lower cost than traditional optical systems.

Marshall's ENR optics process has been successfully demonstrated on instruments like FOXSI.

Learn more about how you can access these capabilities and more provided by Marshall Space Flight Center:

www.nasa.gov/marshallcapabilities



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